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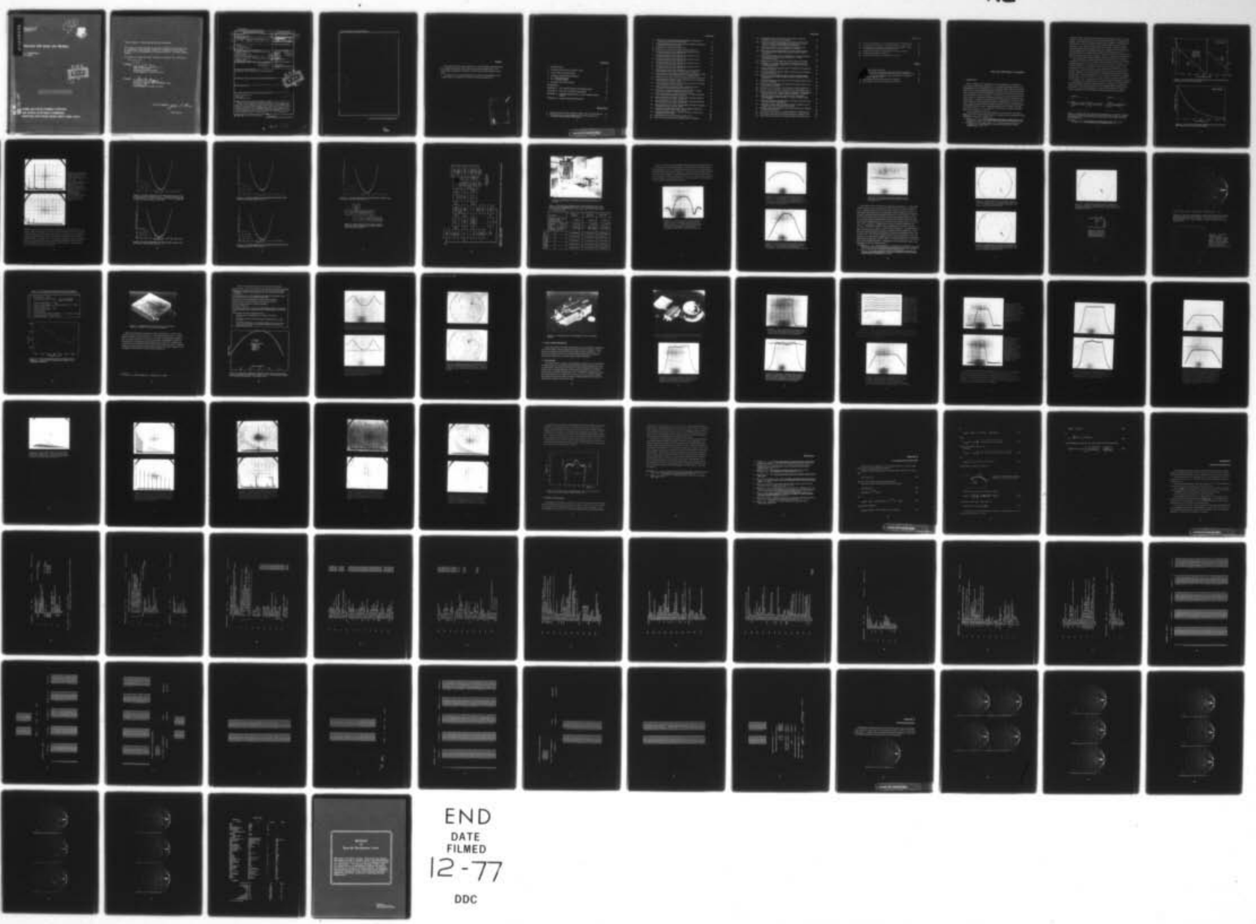

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Ultra-Flat UHF Delay Line Modules

A. J. SLOBODNIK, Jr.
J. H. SILVA

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ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
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Delay modules consisting of surface acoustic wave (SAW) delay lines, equalizers, and amplifiers have been implemented. Ultra-flat (± 0. 1 dB) passband frequency response over a 215 MHz bandwidth centered at 800 MHz has been demonstrated for 7. 5 μ sec of time delay. Module gain of up to 10 dB was achieved. Cascading three modules and using a feedback loop to simulate additional cascade elements demonstrated 500 μ sec of time delay over 200 MHz bandwidth in a linear system.

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Preface

The ability to store RF energy spread over a wide bandwidth for long periods of time is highly desirable for many military and commercial applications. The present paper investigates one particular approach to this general problem of time delay.

The authors wish to take this opportunity to gratefully acknowledge the many valuable inputs of P. Sokoloff in arriving at the scheme presented here.

Contents

Illustrations

Tables

Ultra-Flat UHF Delay Line Modules

1. INTRODUCTION

Delay or storage of RF waveforms over a wide bandwidth can be useful in a large variety of electronics applications. The purpose of the present report is to investigate the use of straightforward, easy to design surface acoustic wave (SAW) delay lines[1] for achieving long time delays (~500 μsec) over a 200 to 250 MHz bandwidth. Unapodized, periodic interdigital transducers are to be used and the use of matching elements will not be allowed. As will be seen, use of a simple delay line design such as this, effectively shifts design complexity to other components in the delay module. In addition, these specifications and requirements imply that a high center frequency of operation and high material coupling factor are necessary in order to ease fractional bandwidth considerations while allowing a sufficient number of interdigital fingers to yield a reasonable insertion loss. Therefore, the high coupling, high velocity, 41.5, X orientation[2] of lithium niobate will be used along with a center frequency of ~800 MHz.

Due to propagation loss this high a frequency will clearly limit the maximum delay which can be achieved without excessive insertion loss and consequent limiting

(Received for publication 1 August 1977)

1. Slobodnik, A. J., Jr. (1973) UHF and Microwave Frequency Acoustic Surface Wave Delay Lines: Design, TR-73-0538, RADC/EEA, Hanscom AFB, Mass. 01731.
2. Slobodnik, A. J., Jr., and Conway, E. D. (1970) New high-frequency high-coupling low-beam steering cut for acoustic surface waves on $LiNbO_3$, Electron. Lett. 6:171-172.

of dynamic range. Thus the use of the modular system shown in Figure 1 must be adopted. Each module consists of a SAW device to provide delay, an equalizer[3] to provide an overall flat bandpass characteristic and an amplifier to compensate for insertion loss. As shown, modules are cascaded to yield the required overall time delay. The overall flat bandpass shape is necessary in order to avoid bandwidth shrinkage problems when the modules are cascaded; thus the equalizers are used to compensate for the interdigital transducer rolloff characteristics.[1] An alternate solution to the rolloff problem—operating the amplifiers in saturation—was rejected since a linear system was desired. In this way multiple simultaneous signals can be handled without intermodulation product or signal capture problems.

Since gain equalizers cannot compensate for fine grain ripple, it was necessary to minimize any systematic occurrence of this effect in the SAW delay lines. The design goal adopted was to achieve no more than 0.1 dB fine grain ripple in each individual delay line. According to Figures 2 and 3 this corresponds to 45 dB suppression of time domain spurious. (See Appendix A for further details.) This is, of course, a worst case since random spurious would tend to cancel between devices. Following a similar argument it is intended to exclude triple transit from consideration as a spurious response. This is justified to the extent that slightly different delay times are used for each module resulting in ripple cancellation between modules. Thus, in applicable cases pulse measurement techniques will be used.

The following two sections of the report will be devoted to a description of each of the components of the delay modules: delay lines, amplifiers, and equalizers. Section 4 will then provide data on the time and frequency domain performance of the modules. This will be followed by a summary and conclusions in Section 5. Finally, appendices have been included to provide additional data of interest.

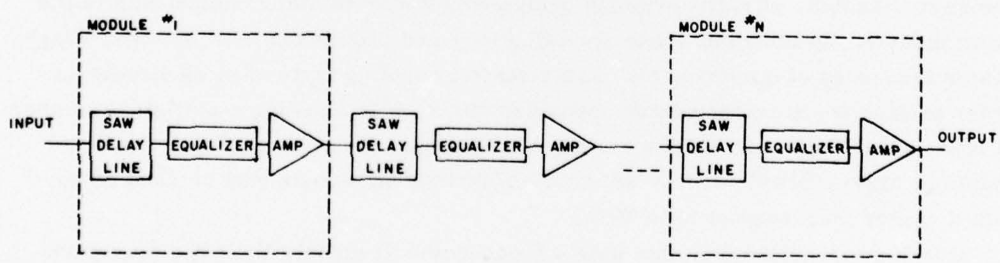

Figure 1. Obtaining Long Time Delays Using Cascaded, Low-Loss Delay Modules. Each module consists of a SAW delay line which provides RF storage, an equalizer which provides an overall flat bandpass characteristic, and an amplifier to overcome insertion loss

3. Erlinger, W.G. (1973) Fine Grain Amplitude Equalization, TR-73-0162, Wavecom, Inc., 9036 Winnetka Ave., Northridge, CA 91324.

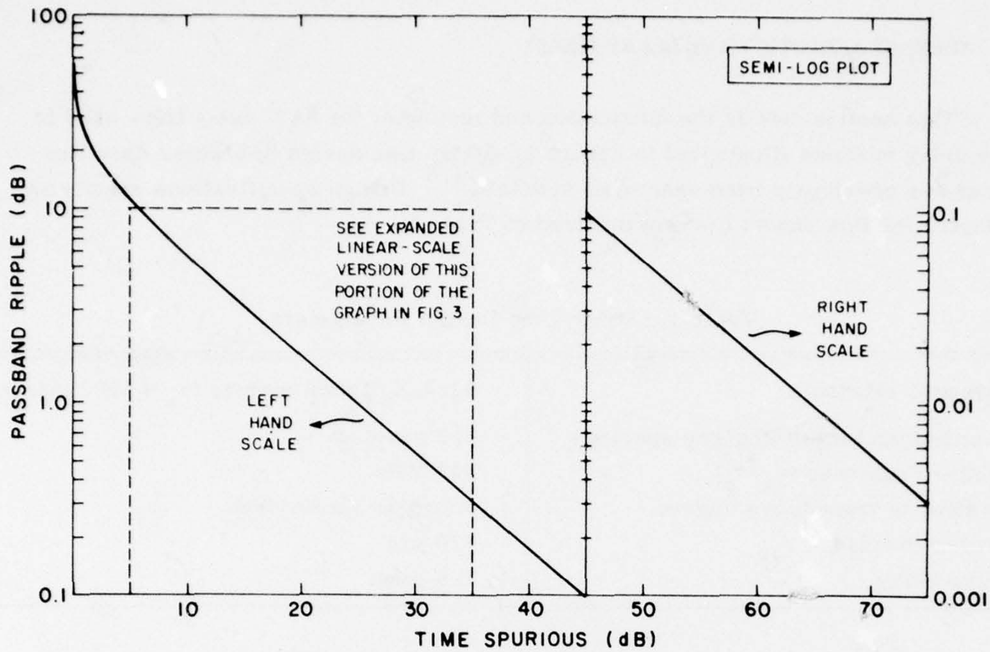

Figure 2. Semi-Log Plot of Conversion Between Time Domain Spurious and Frequency Domain Peak-to-Peak Ripple

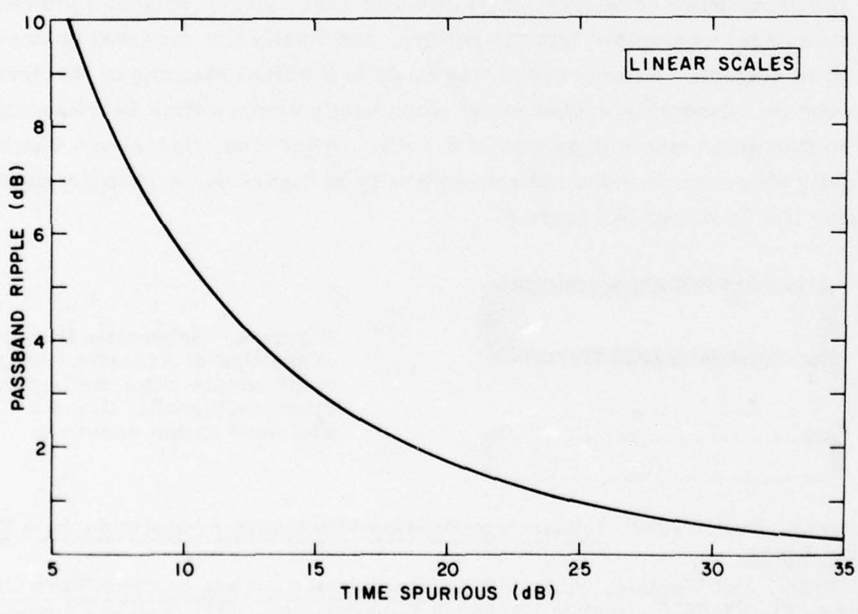

Figure 3. Linear Plot of Conversion Between Time Domain Spurious and Frequency Domain Peak-to-Peak Ripple

2. SURFACE ACOUSTIC WAVE DELAY LINES

This section details the fabrication and testing of the SAW delay lines used in the delay modules illustrated in Figure 1. Delay line design to similar specifications has previously been described in detail.[4,5] Design specifications exactly as adopted for this report are summarized in Table 1.

Table 1. Delay Line Design Parameters

Acoustic substrate	41.5,X lithium niobate (v_s = 4000 m/sec)
Transducer Linewidths/gap spacings	$1.2\ \mu m = \frac{\Lambda_g}{4}$
Center frequency (v_s/Λ_g)	833 MHz
Number of transducer fingers	6 (single electrodes)
Finger overlap	770 μm
Time delay	7.5 μsec

Fabrication was accomplished by contact printing from thin glass negative masters (see Appendix B for master specifications) using the "stripping" or "lift-off" technique.[6] Here photoresist is first spun onto the substrate, the pattern then exposed, the photoresist developed, metal (in this case 200A of chrome followed by 1000A of aluminum) evaporated into the pattern, and finally the unwanted photoresist stripped off in acetone. Extreme care was taken in the final cleaning of the devices since any dirt or island of unwanted metal could easily cause a time spurious signal resulting in fine grain ripple in excess of 0.1 dB. In addition, liberal use was made of an acoustic absorber as indicated schematically in Figure 4. A photograph of a typical delay line is shown in Figure 5.

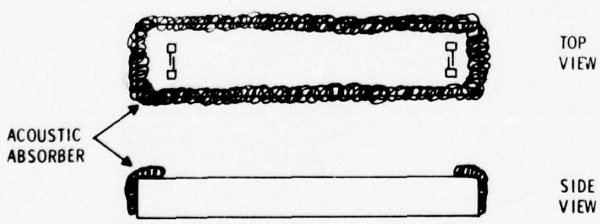

Figure 4. Schematic Illustration of the Use of Acoustic Absorber to Eliminate Edge-Reflection Spurious Signals. Duco® Cement was used as the absorber

4. Armstrong, D. B. (1972) Research to Develop Microwave Acoustic Surface Wave Delay Lines.
5. Wolf, E. D., and Weglein, R. D. (1973) Microwave Acoustic Surface Wave Delay Lines, TR-73-0570, Hughes Research Laboratories, 3011 Malibu Canyon Road, Malibu, CA 90265.
6. Smith, H. I. (1976) Fabrication techniques for surface-acoustic-wave and thin film optical devices, Proc. IEEE 62:1361-3187.

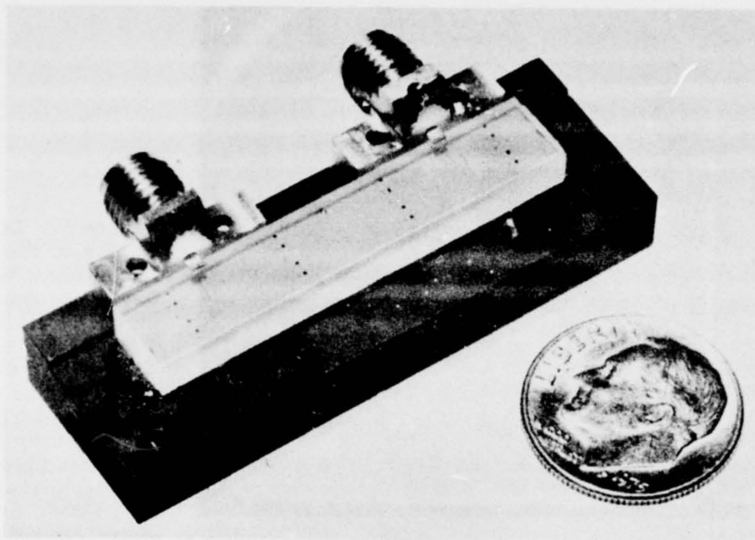

Figure 5. Photograph of a Typical SAW Delay Line. Delay lines used in this report did not have the intermediate taps shown in this photo

Using these techniques several bandpass-ripple/time-spurious-free delay lines were successfully realized. Time domain photos* confirming this fact are shown in Figure 6 and insertion loss vs frequency characteristics for three different delay lines further demonstrating this accomplishment are shown in Figures 7 to 9. The solid line in Figures 7 to 9 represents a least squares 4th order polynomial fit to the experimental data points also shown. Numerical data derived from this fit is given for each delay line in Table 2. In addition, 2nd and 3rd order polynomial fits to the data of Figure 7 are given in Figures 10 and 11 respectively. From this data it is clear that at least a 4th order polynomial is necessary to properly fit the data. Complate numerical printout corresponding to delay line No. 11 is provided in Appendix C together with a listing of the program used for the least squares fit.

Data for Figure 6 were obtained using a standard time domain setup; the major components of which are illustrated in block diagram form in Figure 12. However, in order to obtain insertion loss vs frequency data reproducible to 0.02 to 0.05 dB (necessary if 0.1 dB ripple was to be detected) the precision measurement system illustrated in Figure 13 was devised and used. The heart of this system is the precision variable IF attenuator; that is, the relative insertion loss measurements

*Final time domain testing of delay line No. 12 indicated a time spurious approximately 40 dB down. This was not present during initial testing and it is not known when it first developed.

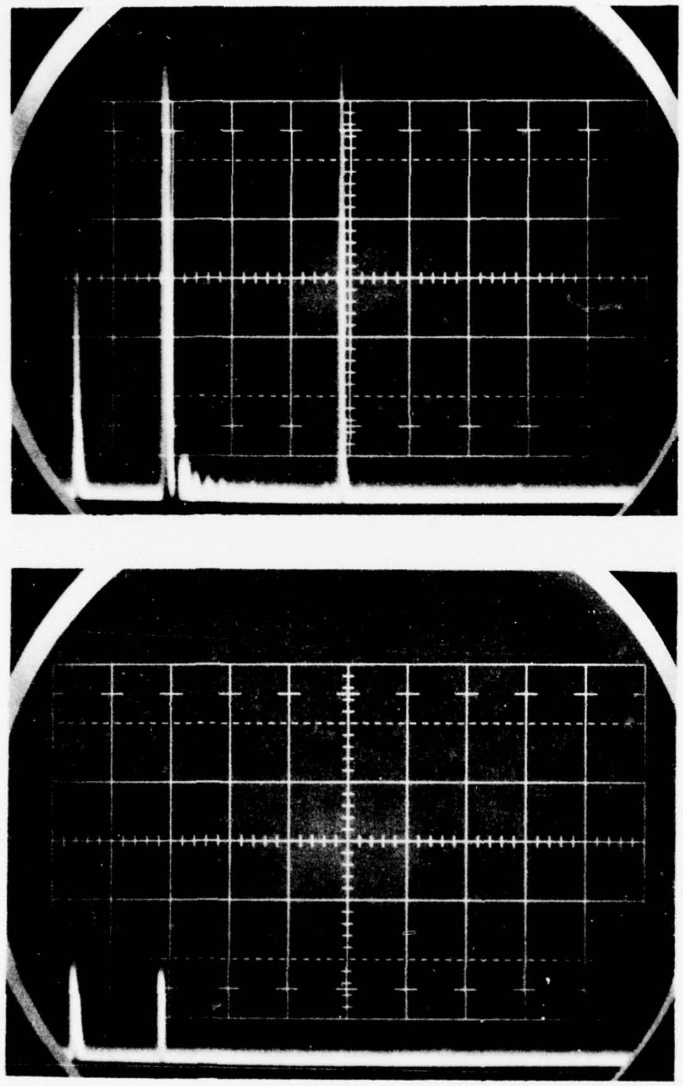

Figure 6. Time Domain Photos of the Response of Delay Line No. 11. Center frequency of input pulse = 821.85 MHz. 5 μsec/div. TOP: Gain setting showing (from left to right) RF leakage, desired SAW delayed output, small spurious signals, and the triple transit response. BOTTOM: Same as above except gain reduced ~60 dB demonstrating the low level of spurious signals present, (more than 60 dB below desired output)

between the delay line path and reference signal path were made at 30 MHz by varying the IF attenuator until the same level was obtained for the two paths. Care was, of course, taken to regulate power levels to insure system linearity. In addition, the reference attenuator was chosen to minimize the required variation in the IF attenuation; that is, a proper "bias" was provided. Note also the use of circulators, isolators, and padding attenuators to minimize VSWR problems and the use of a boxcar integrator to provide accurate pulse comparison levels. A picture of the experimental system is shown in Figure 14.

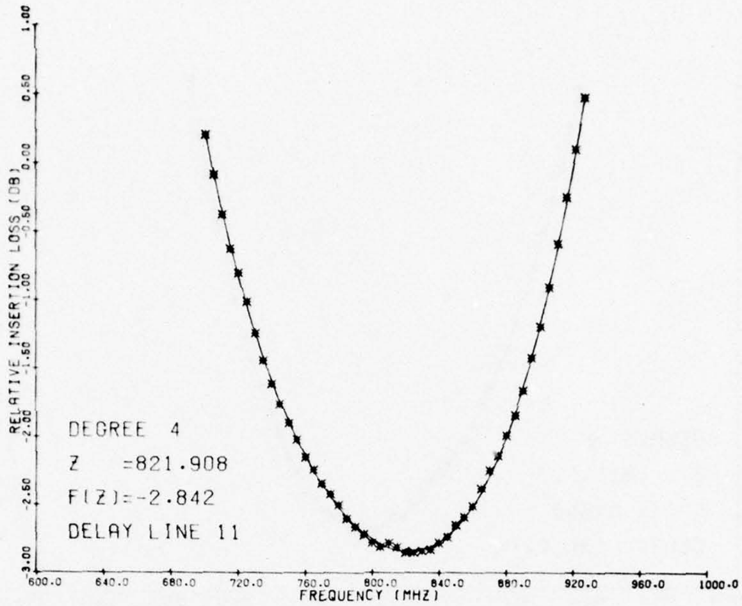

Figure 7. 4th Order Polynomial Fit to Experimental Insertion Loss vs Frequency Data for Delay Line No. 11. Maximum deviation from the fit, 0.0438 dB. Minimum insertion loss, 25.16 dB. Frequency of minimum insertion loss f_o = 821.9 MHz

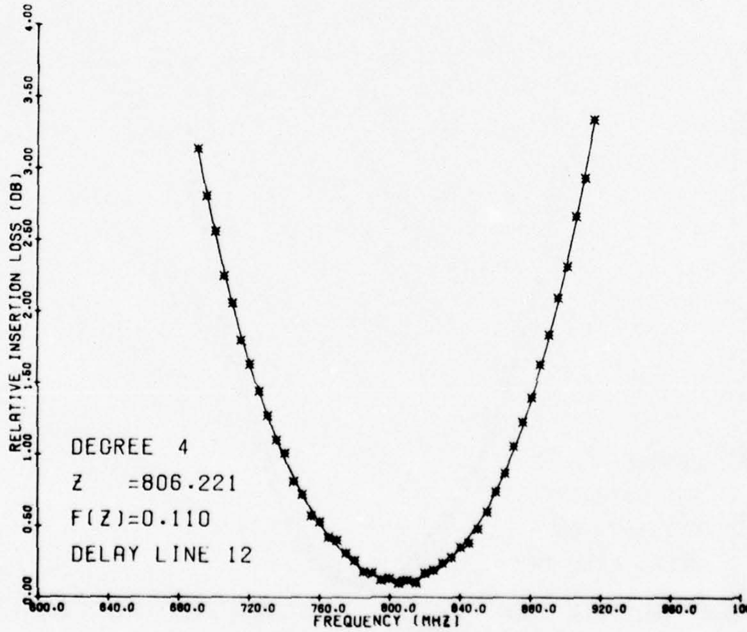

Figure 8. 4th Order Polynomial Fit to Experimental Insertion Loss vs Frequency Data for Delay Line No. 12

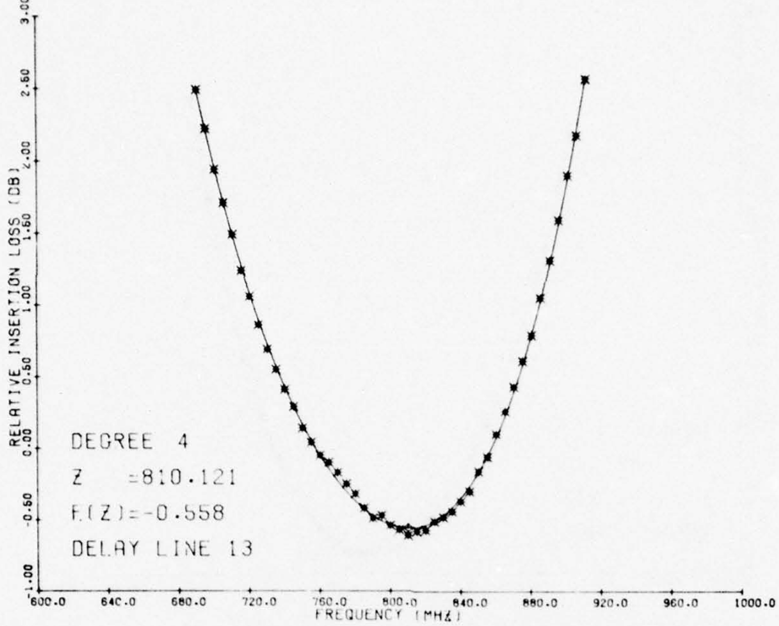

Figure 9. 4th Order Polynomial Fit to Experimental Insertion Loss vs Frequency Data for Delay Line No. 13

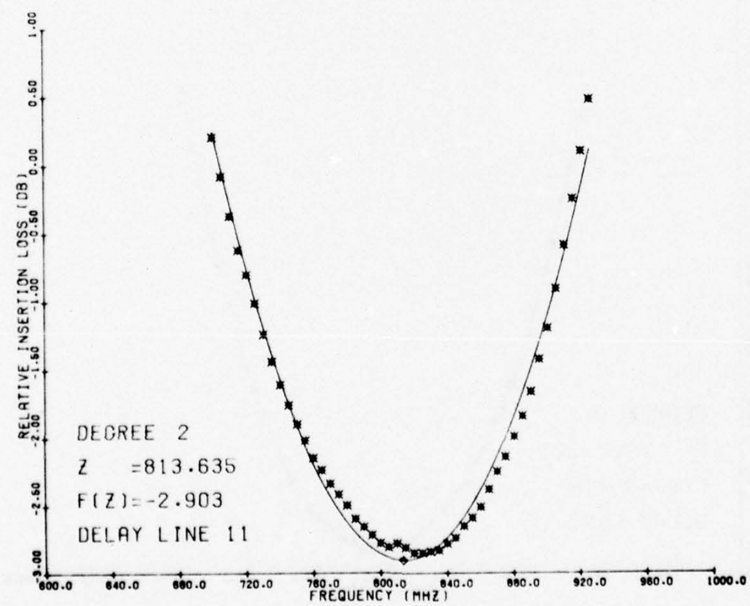

Figure 10. 2nd Order Polynomial Fit to Experimental Insertion Loss vs Frequency Data for Delay Line No. 11

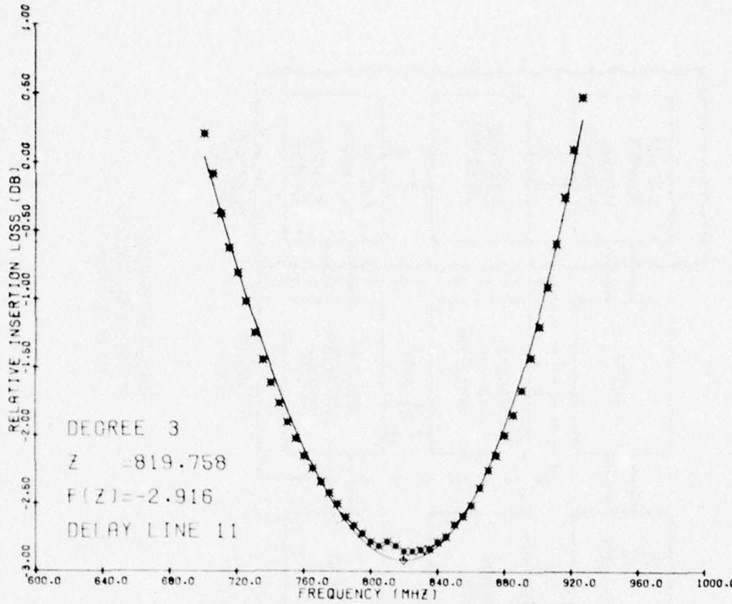

Figure 11. 3rd Order Polynomial Fit to Experimental Insertion Loss vs Frequency Data for Delay Line No. 11

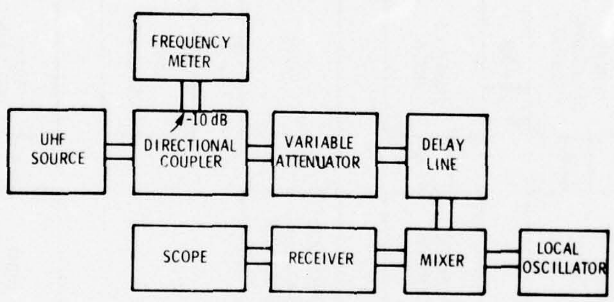

Figure 12. Block Diagram of the Major Components of the Time Domain Measurement System Used to Obtain the Data of Figure 6

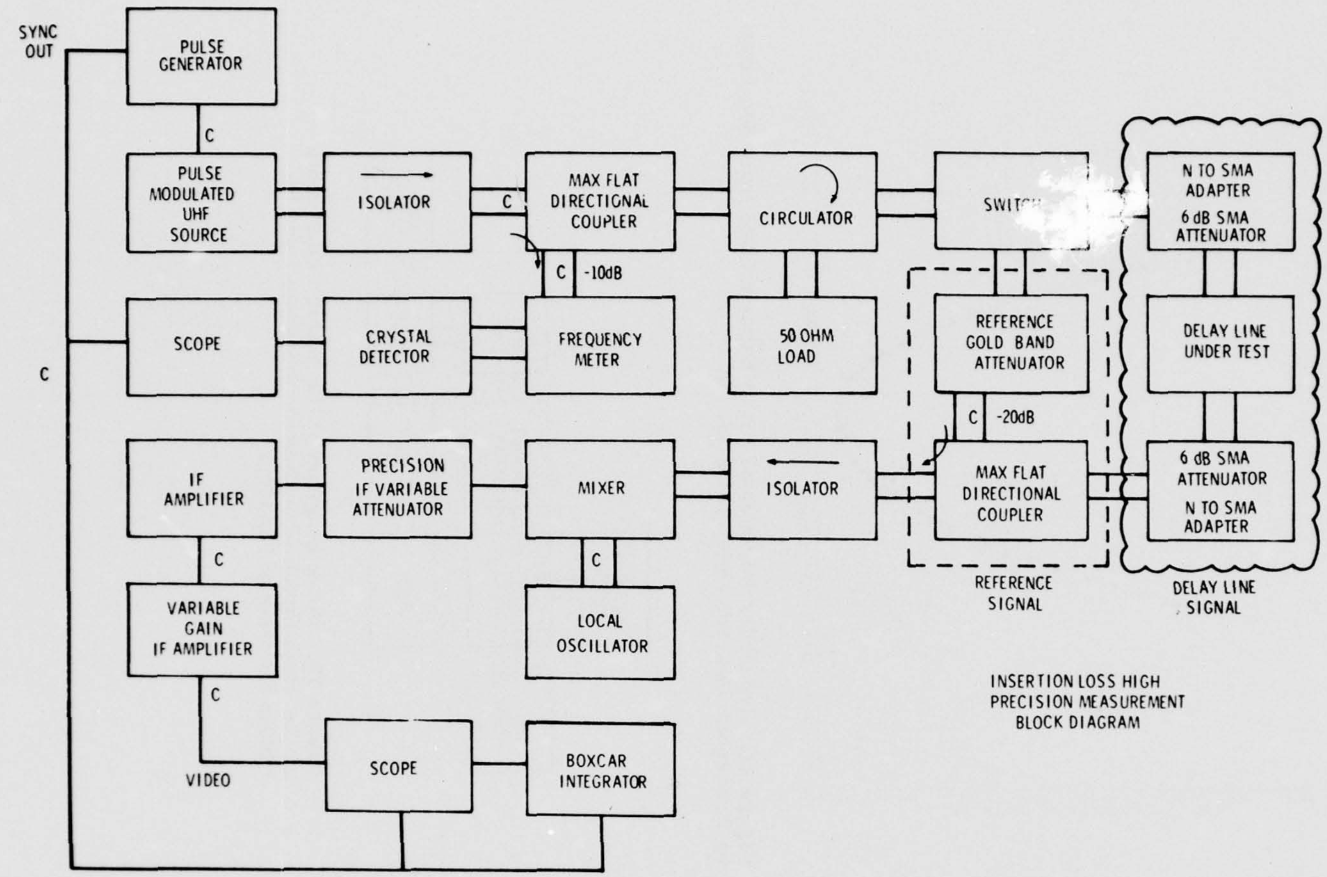

Figure 13. Block Diagram of the Complete High Precision Measurement System Used to Obtain Pulsed Insertion Loss vs Frequency Data

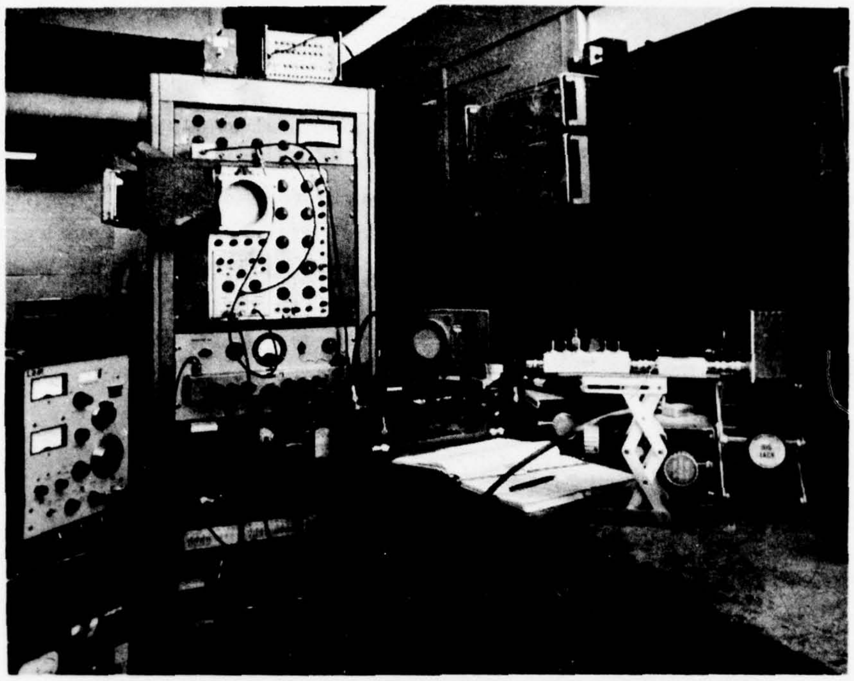

Figure 14. Photograph of the High Precision Measurement System of Figure 13

Table 2. Numerical Data for Three Delay Lines Derived From 4th Order Polynomial Fits to Experimental Insertion Loss vs Frequency Data. Note that RELATIVE INSERTION LOSS = $A_o + A_1F + A_2F^2 + A_3F^3 + A_4F^4$ where F is frequency in MHz

	Parameter		Delay Line No. 11	Delay Line No. 12	Delay Line No. 13
	Maximum Peak Ripple (deviation from 4th order curve)		0.0404 dB	0.0450 dB	0.0624 dB
	Minimum Insertion Loss	Relative	-2.842 dB	0.110 dB	0.558 dB
		Actual	25.16 dB	28.11 dB	~27.4 dB
	Frequency of Mininum Insertion Loss, f_o		821.9 MHz	806.2 MHz	810.1 MHz
Coefficients of the 4th Order Polynomial	A_o		0.21843989E+4	0.18573627E+4	0.16221838E+4
	A_1		-0.10710198E+2	-0.90688318E+1	-0.80285734E+1
	A_2		0.19864610E-1	0.16794319E-1	0.15113774E-1
	A_3		-0.16531944E-4	-0.13981667E-4	-0.12821448E-4
	A_4		0.52051098E-8	0.44142330E-8	0.41304899E-8

A less accurate but more convenient technique for obtaining insertion loss data is, of course, to use a spectrum analyzer. Data obtained in this manner is illustrated in Figures 15 to 17. In order to obtain accurate data and avoid distortion it is essential to use appropriate "padding". In this case 10 dB attenuators were used at both the input and output. It is interesting to note the degree of ripple inherent in this measuring technique as illustrated in Figure 18. Here the spectrum analyzer gain and frequency scale settings of Figure 17 were maintained while substituting a 30 dB precision attenuator for the delay line.

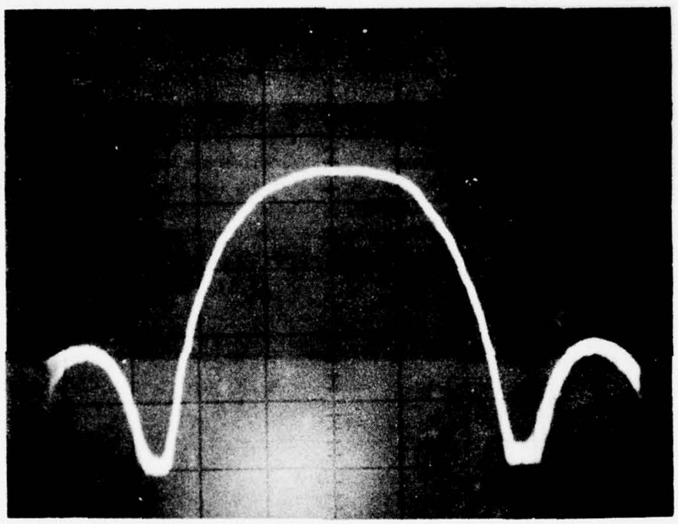

Figure 15. Log Scale Spectrum Analyzer Photo of Insertion Loss vs Frequency Characteristics of Delay Line No. 11. Center vertical crosshatched line corresponds to 800 MHz with horizontal scale 100 MHz/div. Horizontal crosshatched line corresponds to 40 dB with vertical scale 10 dB/div

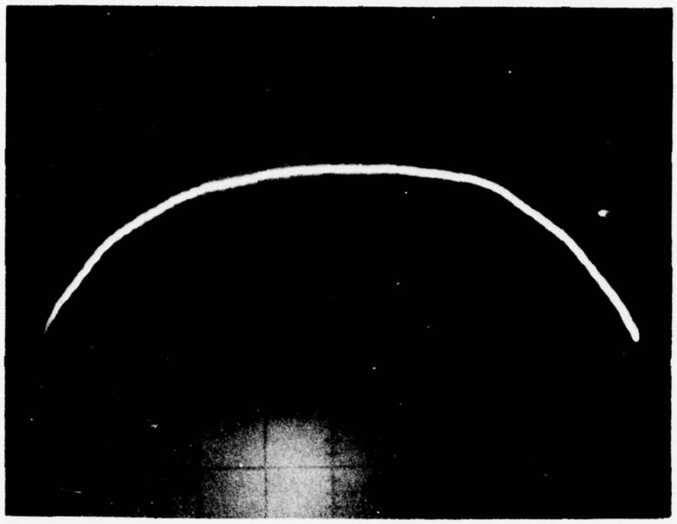

Figure 16. Log Scale Spectrum Analyzer Photo of Insertion Loss vs Frequency Characteristics of Delay Line No. 11. Center vertical crosshatched line corresponds to 800 MHz with horizontal scale 50 MHz/div. Horizontal crosshatched line corresponds to 40 dB with vertical scale 10 dB/div

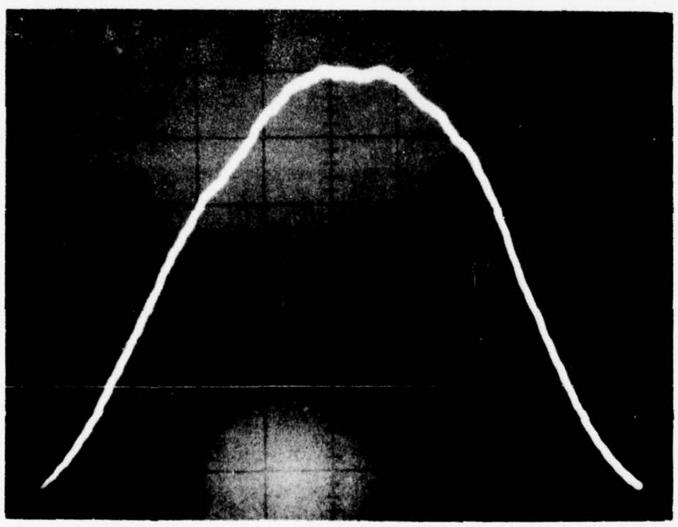

Figure 17. Linear Scale Spectrum Analyzer Photo of Insertion Loss vs Frequency Characteristics of Delay Line No. 11. Center vertical crosshatched line corresponds to 800 MHz with horizontal scale 50 MHz/div

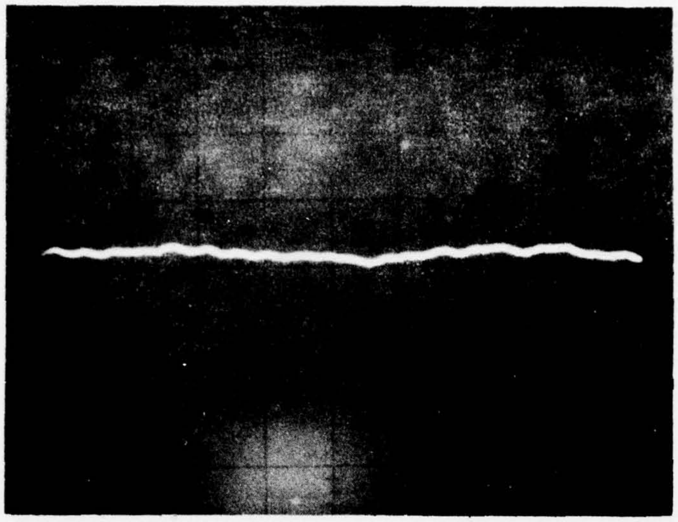

Figure 18. Same Spectrum Analyzer Settings as Used for Figure 17 Except Here a 30 dB Attenuator Replaced the Delay Line

Other delay line data of interest is transducer input impedance. Experimental network analyzer data for the three delay lines under study is given in Figures 19 to 21. Using these results and the experimental insertion loss data of Table 2, a theoretical-experimental study was undertaken in order to determine the parasitic elements[5] associated with the transducer equivalent circuit of Figure 22. Here R and X represent the acoustic radiation resistance and reactance respectively; R_p is a parasitic resistance including the effect of finite transducer metal film resistivity and bulk mode generation; C_x is a parasitic shunt capacitor; and L_w is a parasitic "wire" inductance.[7] Results of this study are included in Appendix D and Table 3. A theoretical impedance plot corresponding to the "best fit" values of $R_p = 90\ \Omega$, $C_x = 0.3$ pF, and $L_w = 10$ nH is shown in Figure 23. Corresponding frequency and time domain plots are shown in Figures 24 and 25 respectively. Note the good agreement between the theoretical and experimental frequency plots of Figures 24 and 15. The parasitic resistance value of 90 Ω corresponds[8] to a film resistivity of 0.57 ohms/square (neglecting any bulk mode contribution) in reasonable agreement with previously measured values of 1.1 ohms/square for similar films with 200A chrome and 800A aluminum. All theoretical data was generated using a well-described second order effects program.[8]

7. Slobodnik, A. J., Jr., Fenstermacher, T. E., Kearns, W. J., Roberts, G. A., and Silva, J. H. (1975) A minimal diffraction lithium tantalate substrate for contiguous SAW Butterworth filters, IEEE Ultrasonics Symposium Proc., pp. 405-407.

8. Sandy, F. (1976) User's Manual for Analysis of Interdigital Transducers for Acoustic Surface Wave Devices, Contract No. F19628-73-C-0277, Raytheon Research Division, Waltham, MA 02154.

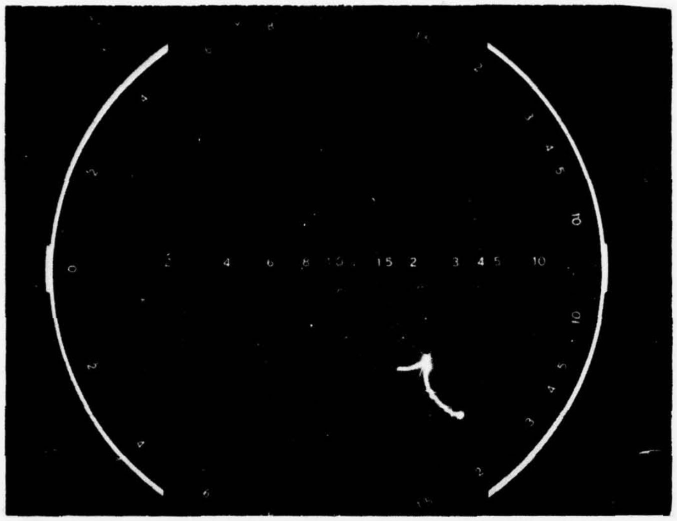

Figure 19. Experimental Network Analyzer Photograph of the Input Impedance of a Transducer From Delay Line No. 11. Frequency sweeps from 600 to 1000 MHz. The marker (dark dot) signifies 800 MHz

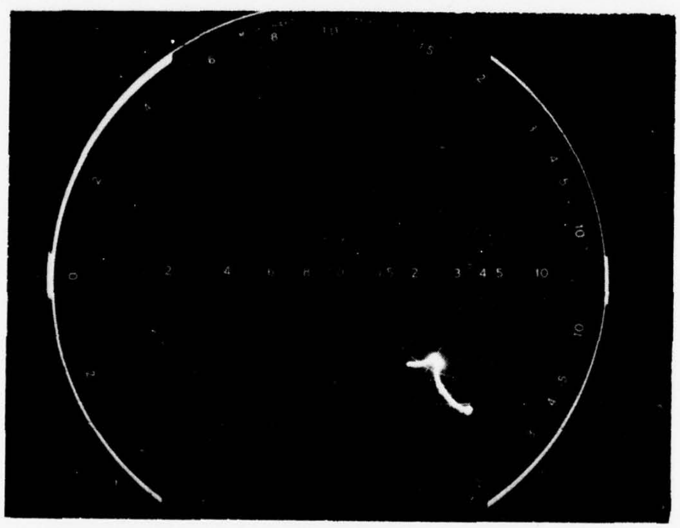

Figure 20. Experimental Network Analyzer Photograph of the Input Impedance of a Transducer From Delay Line No. 12. Frequency sweeps from 600 to 1000 MHz. The marker (dark dot) signifies 800 MHz

Figure 21. Experimental Network Analyzer Photograph of the Input Impedance of a Transducer From Delay Line No. 13. Frequency sweeps from 600 to 1000 MHz. The marker (dark dot) signifies 800 MHz

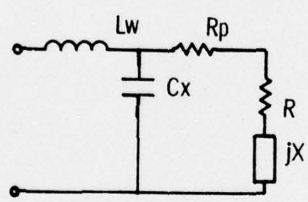

Figure 22. Equivalent Electrical Circuit of an Interdigital Transducer Including Elements to Model Parasitic Effects

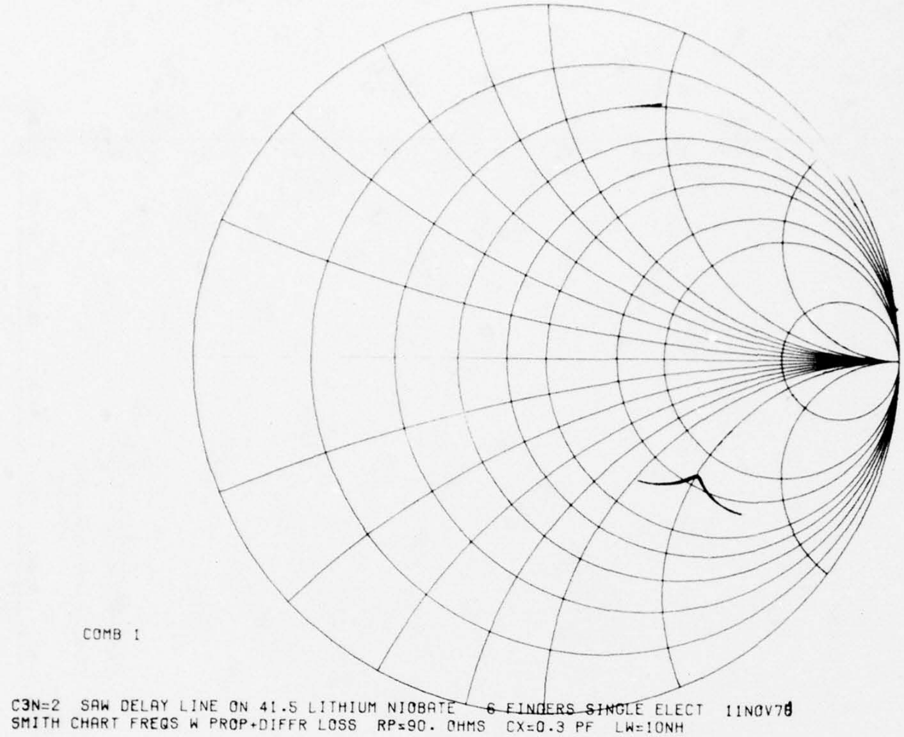

Figure 23. Theoretical Input Impedance Plots of the Interdigital Transducer Used for the Delay Lines of this Report. Best fit parasitic element values are included as follows: R_p = 90 ohms, C_x = 0. 3 pF, and L_W = 10 nH. SAW substrate is 41. 5, X lithium niobate. Compare to experimental data of Figures 19 to 21

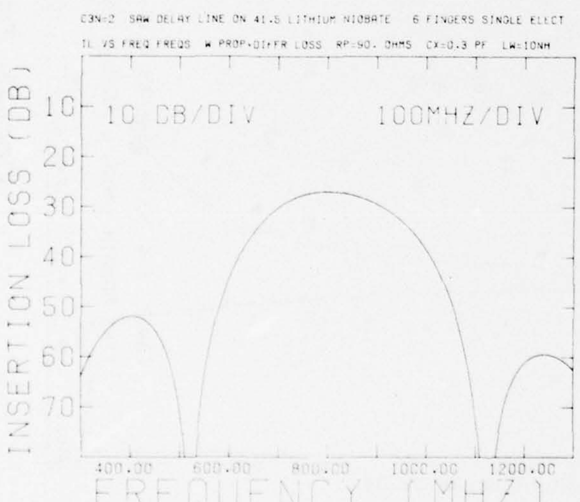

Figure 24. Theoretical Insertion Loss vs Frequency Plot for a Delay Line as Described in This Report. Best fit parasitic element values, propagation loss, and diffraction loss included. Compare to experimental data of Figure 15

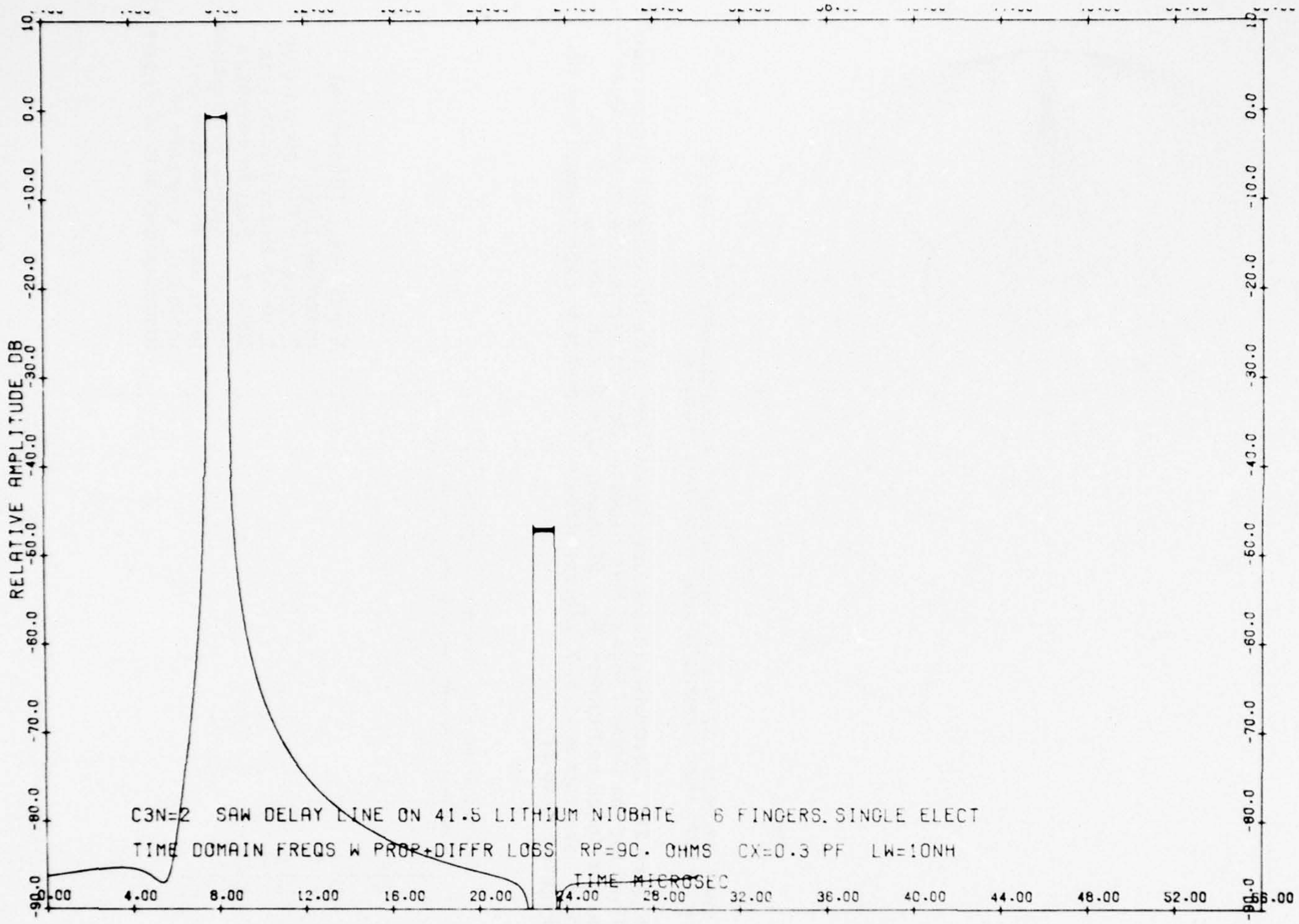

Figure 25. Theoretical Time Domain Response of Delay Line

Table 3. Delay Line Theoretical Insertion Loss at 800 MHz as a Function of Parasitic Element Values

R_p (ohms)	C_x (pF)	L_w(nH)	IL (dB) (at 800 MHz)
0	0	0	24.24
150	0	0	33.36
150	0.3	0	33.51
150	0.6	0	33.74
150	0.9	0	34.02
75	0.3	0	29.11
75	0.6	0	29.41
75	0.9	0	29.76
75	0.3	5	27.33
75	0.3	10	25.65
75	0.3	15	24.24
75	0.6	5	27.25
75	0.6	10	25.22
75	0.6	15	23.62
150	0.6	5	32.06
150	0.6	10	30.48
150	0.6	15	29.14
150	0.3	5	32.27
150	0.3	10	31.12
150	0.3	15	30.14
90	0.3	10	26.86
90	0.3	8	27.45
90	0.4	8	27.30

3. AMPLIFIERS AND EQUALIZERS

As indicated in Figure 1 each delay module includes an amplifier and an equalizer in addition to the SAW delay line described above. These two additional components were purchased commercially, although the equalizers required prior development.[3]

Amplifier specifications are shown in Table 4. Note the concern with flatness in order to avoid fine grain ripple as discussed in the delay line section. Point by point frequency data on an earlier (30 dB gain over a slightly different frequency range) amplifier design is shown in Figure 26. Low ripple was achieved. A photograph of one of the final amplifiers* is shown in Figure 27.

*Locus, Inc., Box 740, 1517 Science Street, State College, PA 16801.

Table 4. Specifications Used for Procurement of Amplifiers. Note the center frequency of 800 MHz and bandwidth of 240 MHz

A.	Minimum gain: 40 dB
B.	Gain flatness (680 to 920 MHz): ± 0.1 dB (if possible achieve ± 0.05 dB)
C.	Maximum noise figure: 3.5 dB
D.	Minimum power output for 1 dB gain compression: + 10 dBm
E.	Maximum input VSWR: 1.25
F.	Maximum output VSWR: 1.25
G.	OSM connectors
H.	Maximum size (excluding connectors): 7-1/2 cubic in. (no min)
I.	Maximum weight: 3.5 oz (no min)

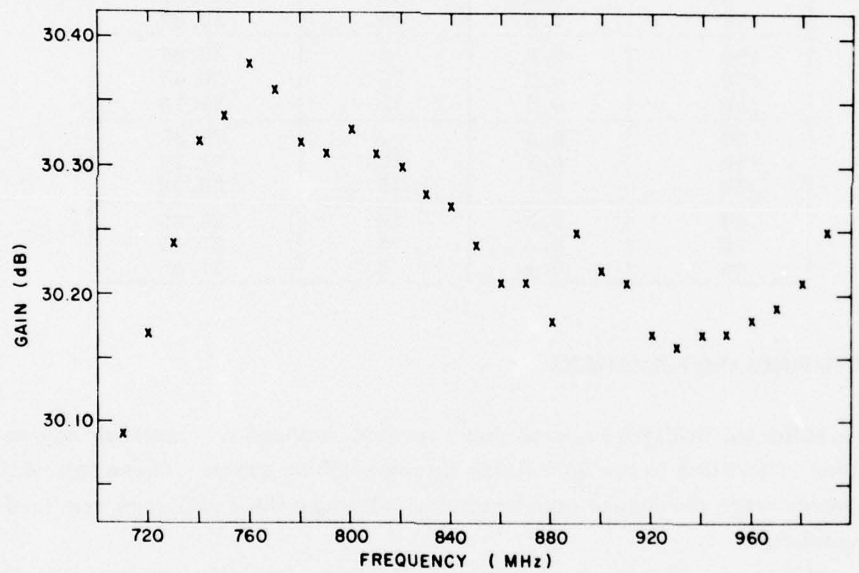

Figure 26. Point by Point Measurement of Amplifier Gain vs Frequency. A circuit similar to that shown in Figure 13 was used to obtain this data

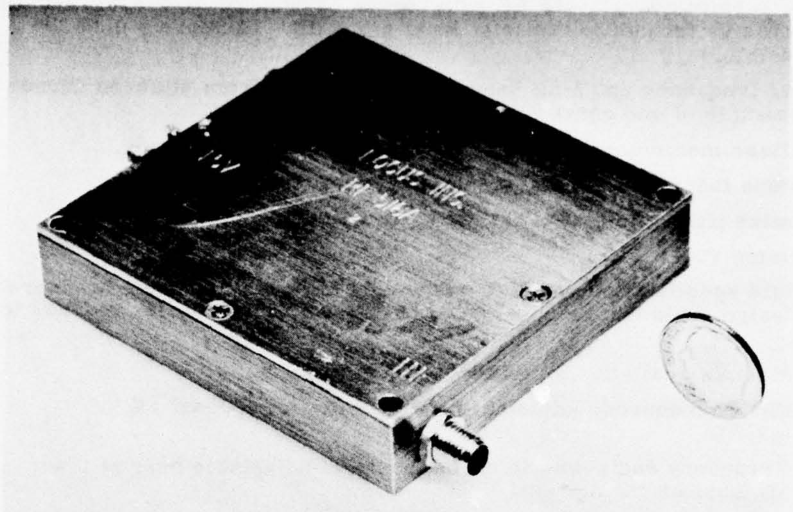

Figure 27. *Photograph of One of the Flat Gain-vs-Frequency 40 dB Gain Amplifiers Used for the Delay Modules*

Equalizer specifications are shown in Table 5 and Figure 28. A linear scale spectrum analyzer photo of equalizer No. 13 (designed for delay line No. 13) in as-delivered condition is shown in Figure 29. The effect of instrumentation ripple is shown in Figure 30 where a trace (with adjusted gain) corresponding to removal of the equalizer is superimposed on the equalizer trace of Figure 29. Padding used in both cases here consisted of 20 dB attenuators at both input and output. The input impedance characteristics of each port of this equalizer are shown in Figure 31 and a photograph of the equalizer[†] itself is shown in Figure 32.

[†] Wavecom, Inc., 9036 Winnetka Ave., Northridge, CA 91324.

Table 5. Specifications Used for Procurement of Equalizers

Equalizers to compensate AF gain curves to produce an overall system response vs frequency flat to at least ± 0.1 dB. (Achieve ± 0.05 dB if possible.)
Center frequency and 3 dB bandwidth to be taken from attached curves (an example of one curve is given in Figure 28).
Equalizer maximum attenuation to occur at center frequency.
Insertion loss at end (3 dB) points no greater than 2.0 dB.
Minimize phase distortion caused by equalizer.
Maximum VSWR 1.5
No rigid specifications on size and weight although minimum is desired and design goals can be considered to be less than 8 cubic in. and less than 2 oz.
Adjustments available on finished devices:
Center frequency adjustable over a range of at least 5% (±2.5%).
Frequency end points (3 dB band edges) adjustable over at least 5% (±2.5%).
Minor trim adjustments to compensate deviations from AF curves of up to 0.3 dB. (Note that these deviations will be regular and not fine grain ripple.)

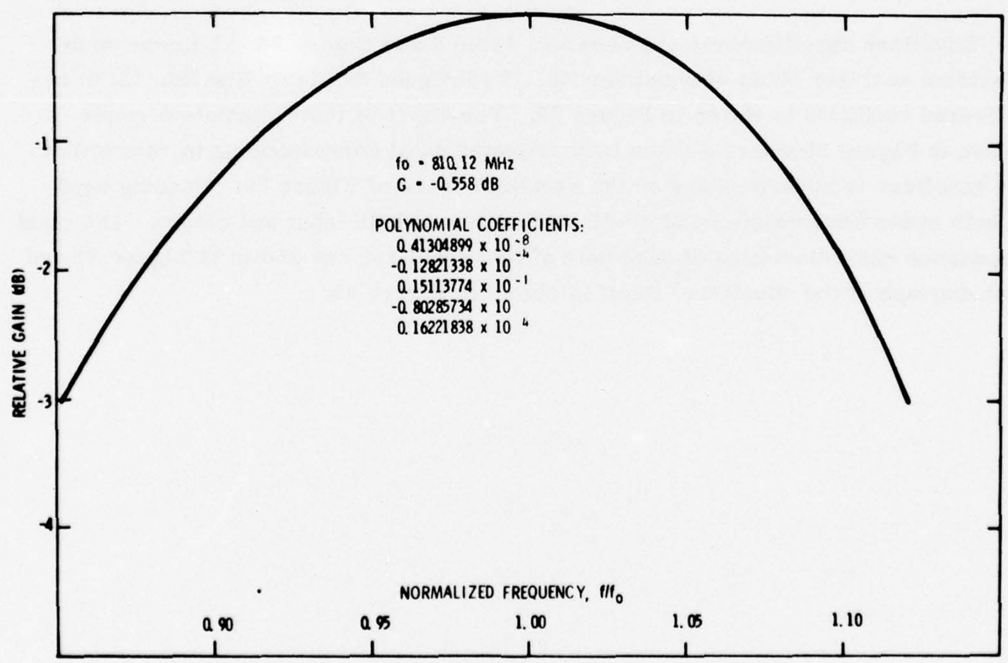

Figure 28. Example of a 4th Order Polynomial Curve Fitted to the Insertion Loss vs Frequency Characteristics of Delay Line No. 13 as Supplied to Vendors With Equalizer Specifications. See Tables 2 and 5

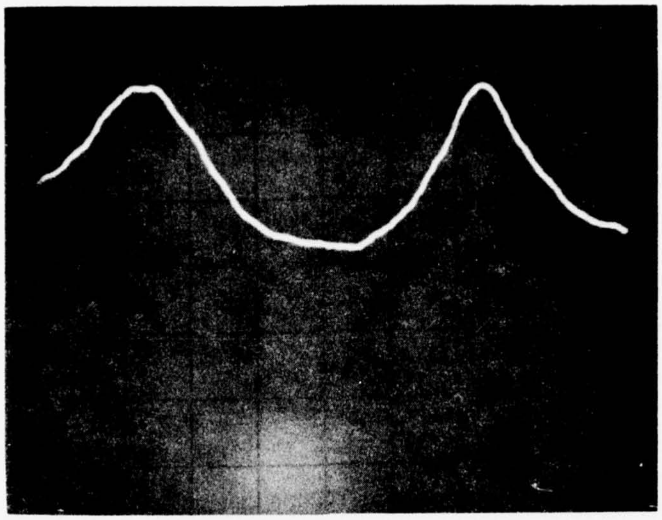

Figure 29. Linear Scale Insertion Loss vs Frequency Characteristics of Gain Equalizer No. 13 As-Received From Wavecom. Center vertical crosshatched line corresponds to 800 MHz with horizontal scale 50 MHz/div

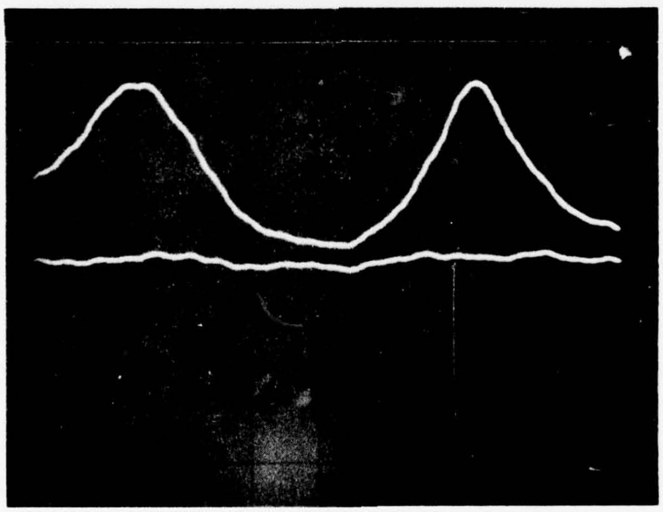

Figure 30. Illustration of Instrumentation Ripple by Means of Superimposed Trace With Equalizer Removed (and gain reduced) on Photo of Figure 29. Center vertical crosshatched line corresponds to 800 MHz with horizontal scale 50 MHz/div

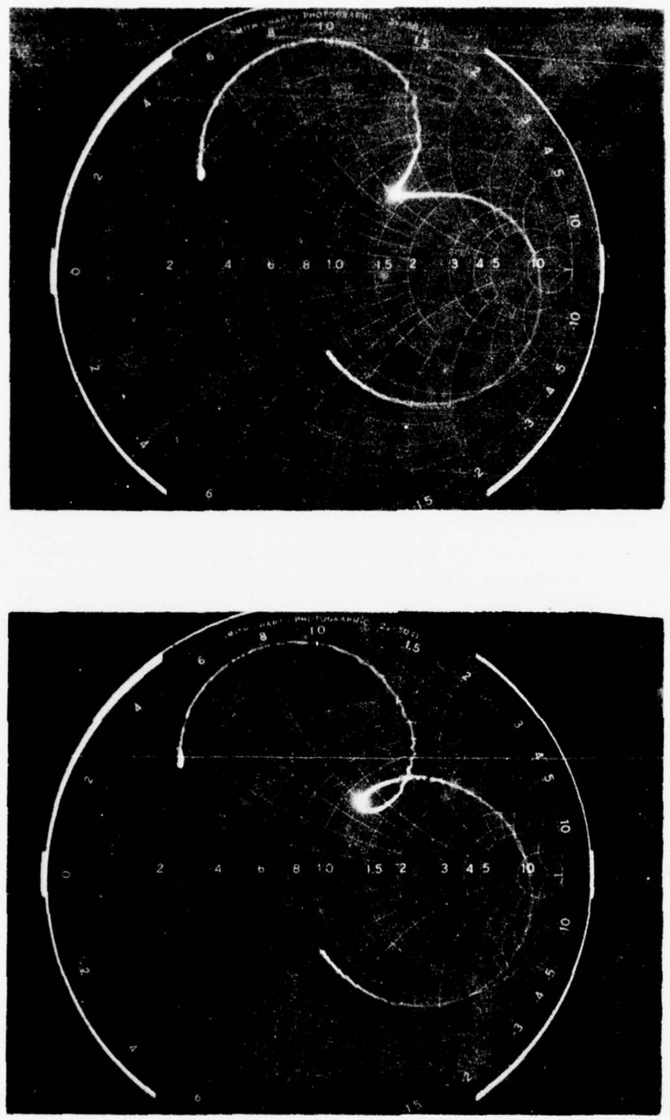

Figure 31. Experimental Network Analyzer Photographs of the Input Impedance Characteristics of Each Port of Equalizer No. 13 With As-Received Settings. Frequency sweeps from 600 to 1000 MHz with marker (dark dot) at 800 MHz

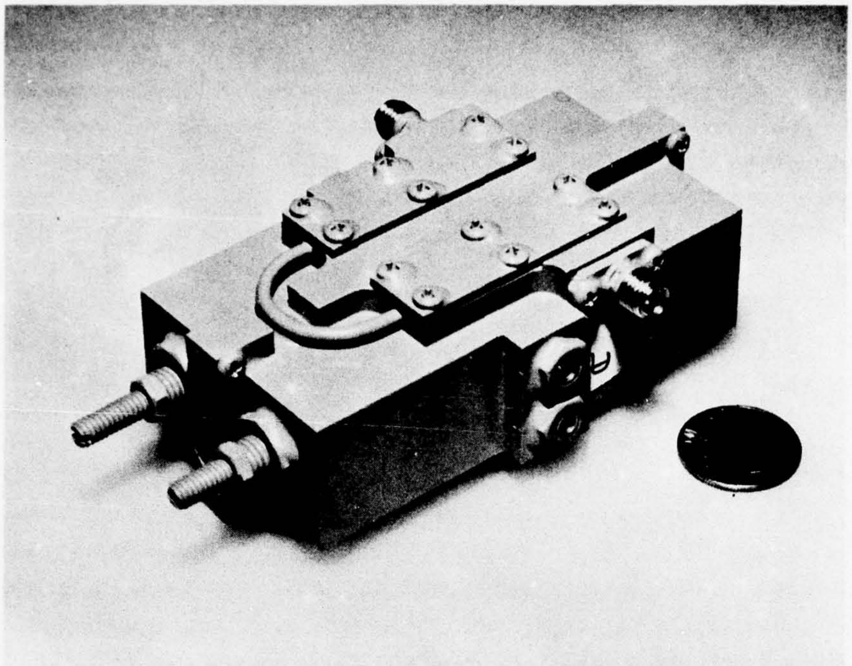

Figure 32. Photograph of One of the Equalizers Used for the Delay Modules

4. OVERALL MODULE PERFORMANCE

Having described the individual characteristics of each of the three components of the delay module, overall module performance will now be discussed. That is, the three components are interconnected in series as shown in Figure 33. Note that in some cases use of small (1 to 6 dB) attenuators between components improved performance; that is, reduced ripple at a given bandwidth.

4.1 Individual Modules

The insertion loss vs frequency characteristics of module No. 11 are illustrated in Figures 34 and 35. The equalizer was adjusted for optimum flatness over maximum bandwidth. Performance is excellent. An ultra low ripple, flat bandpass was achieved over a 230 MHz bandwidth. As illustrated in Figure 36 much of the observed ripple is caused by instrumentation; so it is difficult to quantitatively specify the ripple achieved by the module alone. However, we do note that data obtained from using the linear scale spectrum analyzer calibration photo shown in Figure 37 indicates total ripple of the order of 0. 3 dB

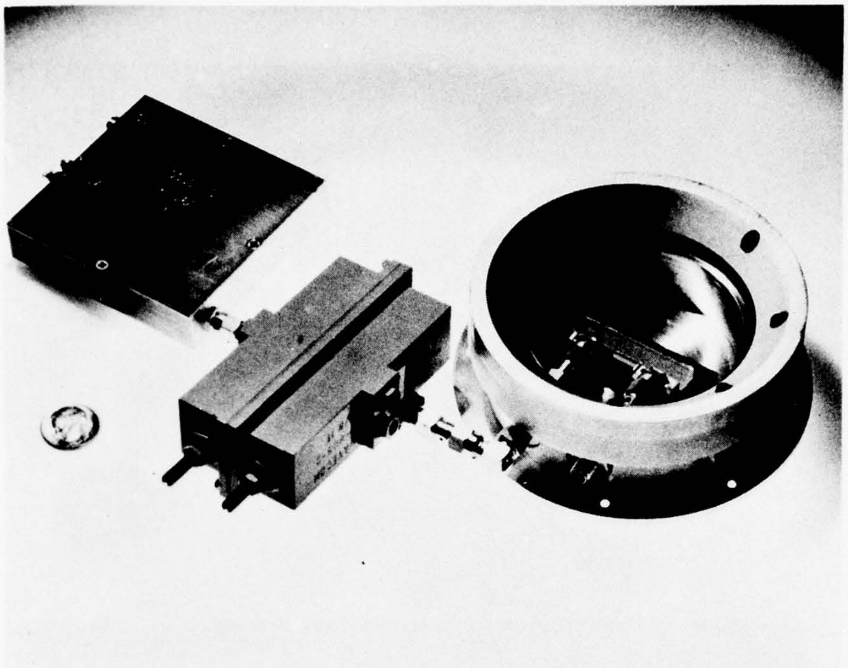

Figure 33. Photograph of a Complete Delay Module Consisting of (from left to right) an Amplifier, an Equalizer, and a SAW Delay Line in an Air Tight Test Can

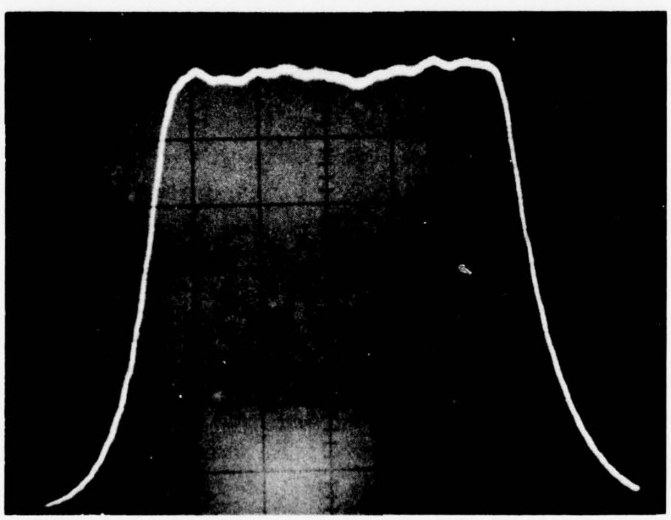

Figure 34. Linear Scale Spectrum Analyzer Photo of Frequency Characteristics of Delay Module No. 11. Center vertical crosshatched line corresponds to 800 MHz with horizontal scale 50 MHz/div

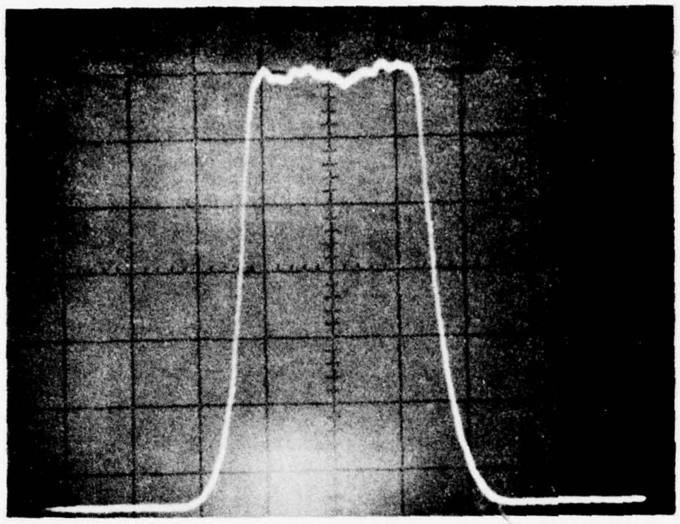

Figure 35. Linear Scale Spectrum Analyzer Photo of Frequency Characteristics of Delay Module No. 11. Center vertical crosshatched line corresponds to 800 MHz with horizontal scale 100 MHz/div

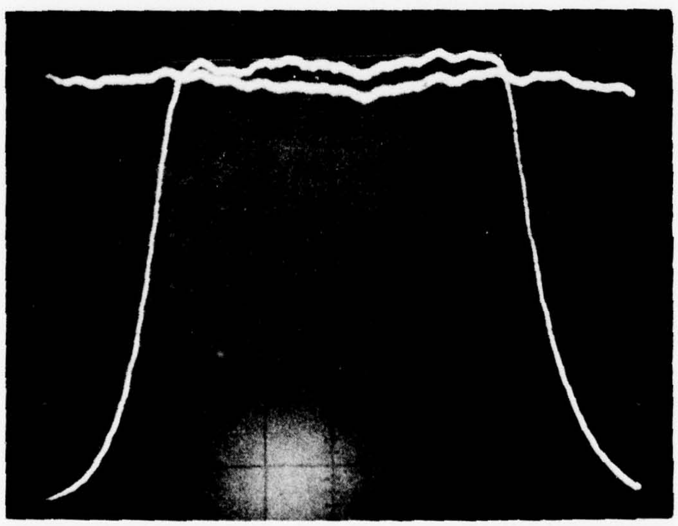

Figure 36. Illustration of Instrumentation Ripple by Means of Superimposed Trace With Delay Module Removed (and gain adjusted) on Photo of Figure 34. Center vertical crosshatched line corresponds to 800 MHz with horizontal scale of 50 MHz/div

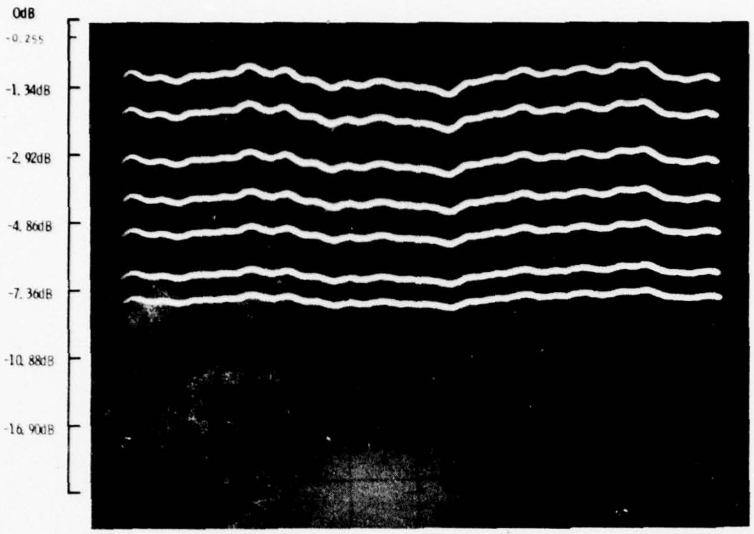

Figure 37. Linear Scale Spectrum Analyzer Photo With Corresponding dB Values Shown for Reference. The traces on the photo correspond to the following experimental attenuator values (from top to bottom): 0 dB, 1 dB, 2 dB, 3 dB, 4 dB, 5 dB, and 6 dB. Center vertical crosshatched line corresponds to 800 MHz with horizontal scale 50 MHz/div

Additional insertion loss vs frequency data for module No. 11 is given in Figures 38 to 40; here on a calibrated log scale. This module provides approximately 10 dB gain. Thus longer time delays are possible within each module while still maintaining overall low insertion loss.

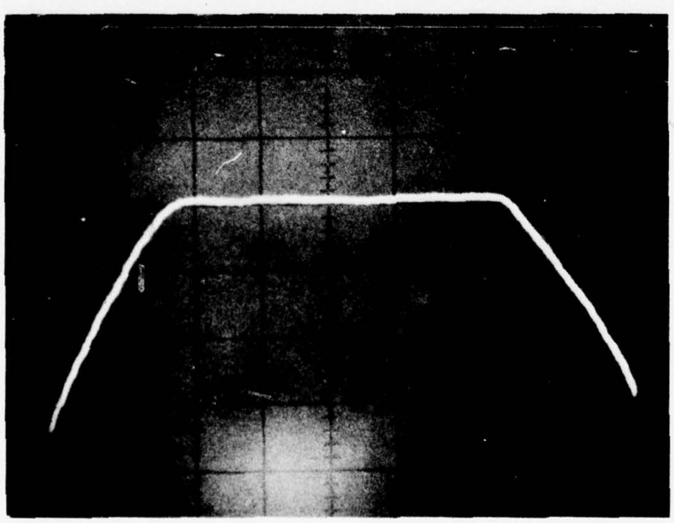

Figure 38. Insertion Loss vs Frequency Characteristics of Delay Module No. 11 on a Calibrated dB Scale. Center horizontal crosshatched line corresponds to 0 dB with 10 dB/div on vertical scale. Note module provides approximately 10.5 dB gain. Center vertical crosshatched line corresponds to 800 MHz with horizontal scale 50 MHz/div

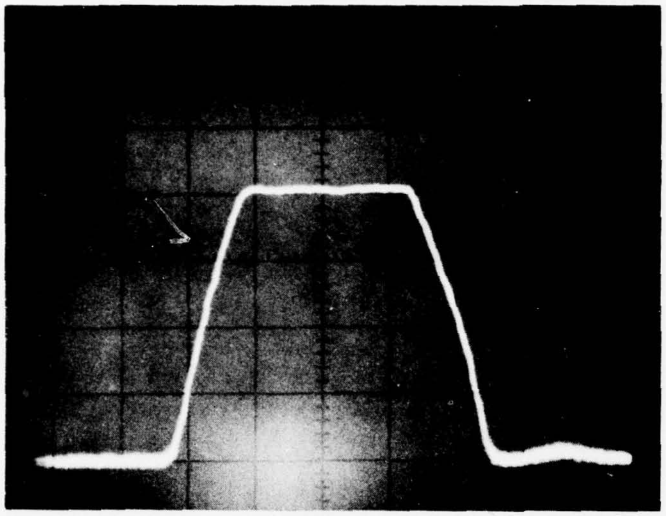

Figure 39. Insertion Loss vs Frequency Characteristics of Delay Module No. 11. Vertical scale 10 dB/div with center horizontal cross-hatched line corresponding to 0 dB insertion loss. Horizontal scale 100 MHz/div with center vertical crosshatched line corresponding to 800 MHz

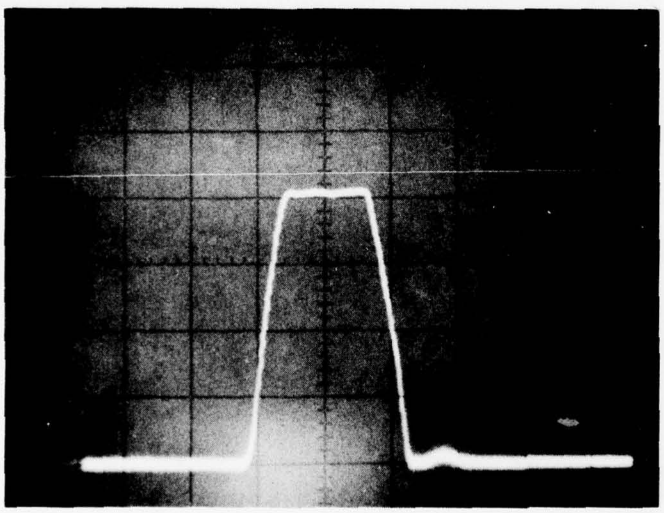

Figure 40. Insertion Loss vs Frequency Characteristics of Delay Module No. 11. Vertical scale 10 dB/div with center horizontal crosshatched line corresponding to 0 dB insertion loss. Horizontal scale 200 MHz/div with center vertical crosshatched line corresponding to 800 MHz. The delay module makes a good bandpass filter

Frequency characteristics of delay modules No. 13 and No. 12 (corresponding to Figures 34 and 38 for module No. 11) are shown in Figures 41 and 42. For these modules superior performance was obtained by using low value (4 dB for module No. 13 and 3 dB for module No. 12) attenuators between the delay lines and equalizers. Total ripple achieved for module No. 13 was ~0.2 dB while a larger value of ~0.5 dB for module No. 12 was obtained.

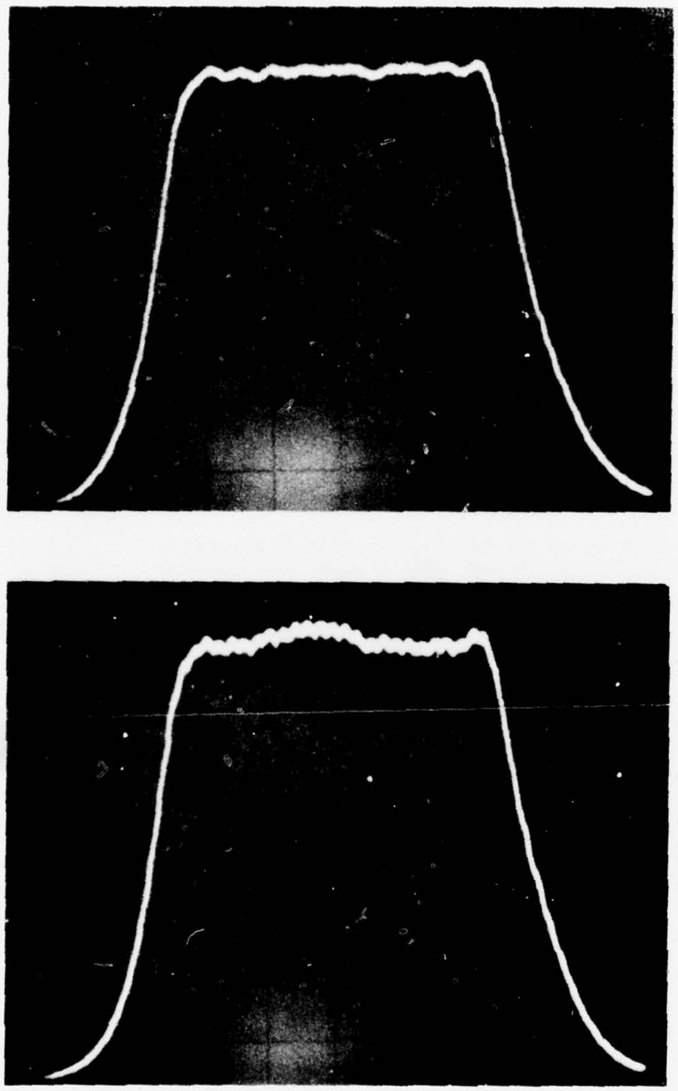

Figure 41. Linear Scale Spectrum Analyzer Photos of Frequency Characteristics of Delay Module No. 13 (top) and Delay Module No. 12 (bottom). Center vertical crosshatched line corresponds to 800 MHz with horizontal scale 50 MHz/div. Compare to Figure 34

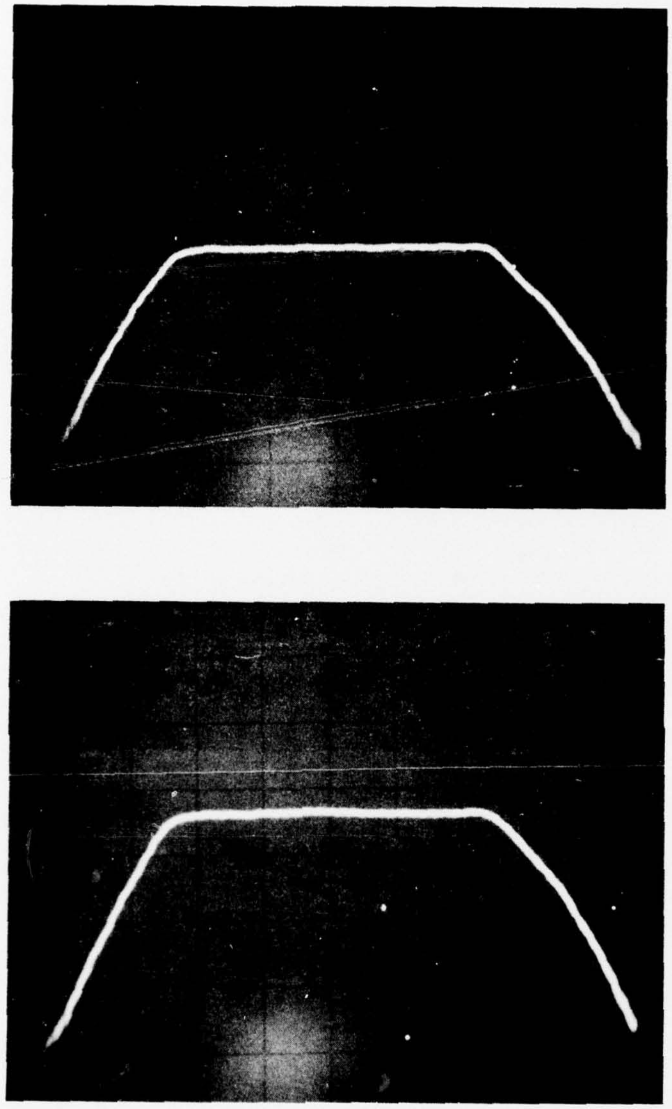

Figure 42. Calibrated Log Scale Spectrum Analyzer Photos of Frequency Characteristics of Delay Module No. 13 (top) and Delay Module No. 12 (bottom). A 4 dB attenuator was used between the delay line and equalizer in Module No. 13 and a 3 dB attenuator in Module No. 12. Vertical scale 10 dB/div with horizontal crosshatched line corresponding to 0 dB. Horizontal scale 50 MHz/div with vertical center crosshatched line corresponding to 800 MHz. Compare to Figure 38

4.2 Cascaded Modules

At this point we cascade the three modules as per the goal outlined in Figure 1. Frequency characteristics are shown in Figures 43 and 44. Again, performance is good with ripple estimated at 0.5 dB. Since it is our intention to provide feedback as illustrated schematically in Figure 45 in order to simulate the cascading of many modules, overall gain had to be reduced to less than unity. This was accomplished by placing 3 dB attenuators at the input (before delay line) to each module and a 10 dB attenuator between the directional couplers. The feedback loop was, of course, broken in order to obtain the data of Figures 43 and 44.

The overall time domain performance of the cascaded modules of Figure 45 is illustrated in Figures 46 to 50. Here input consisted of an ~0.5 μsec RF pulse centered at approximately 830.7 MHz, this is the first pulse in the top photo of each figure. Although delays of the order of 2 msec are illustrated, our interest will be concentrated in the 500 μsec range. Here input pulse shape is fully maintained as illustrated by comparing Figures 49 and 50 and insertion loss vs frequency characteristics are expected to be reasonable. Some spurious signals attributed to triple transit are noticeable (see Figures 48 and 50) since the three present delay lines were fabricated from a single mask for convenience. Thus all time delays were identical preventing triple transit cancellation.

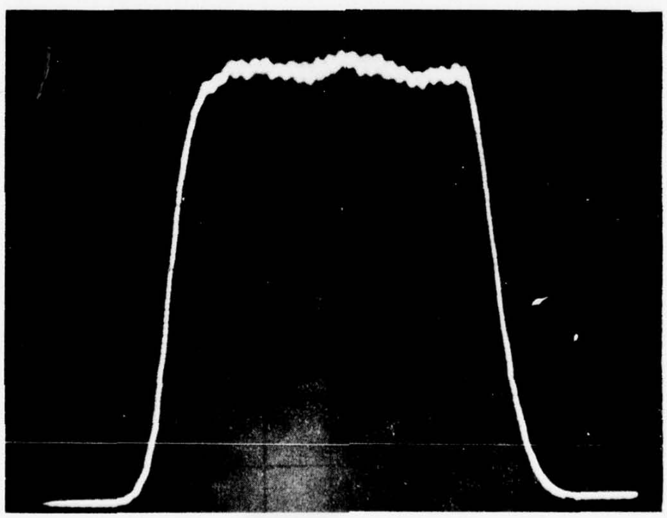

Figure 43. Linear Scale Spectrum Analyzer Photo of Frequency Characteristics of Three Cascaded Delay Modules. Center vertical crosshatched line corresponds to 800 MHz with horizontal scale 50 MHz/div

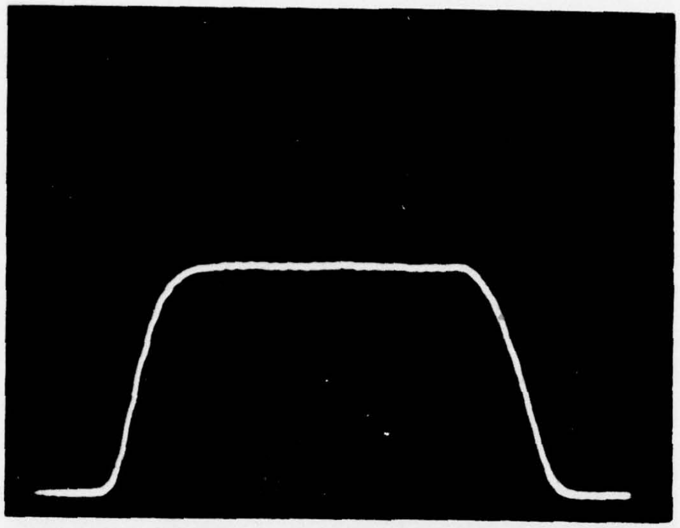

Figure 44. Calibrated Log Scale Spectrum Analyzer Photo of Insertion Loss vs Frequency of Three Cascaded Delay Modules. Extra attenuation added to reduce gain below unity for later use in feedback loop. Vertical scale 10 dB/div with horizontal crosshatched line corresponding to 0 dB. Horizontal scale 50 MHz/div with vertical center crosshatched line corresponding to 800 MHz

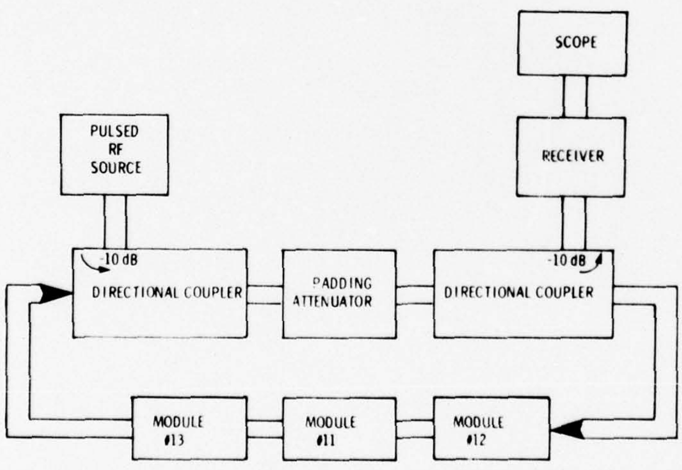

Figure 45. Schematic Diagram of Feedback Loop Used to Simulate the Cascading of Many Delay Modules. Less than unity loop gain maintains a linear system

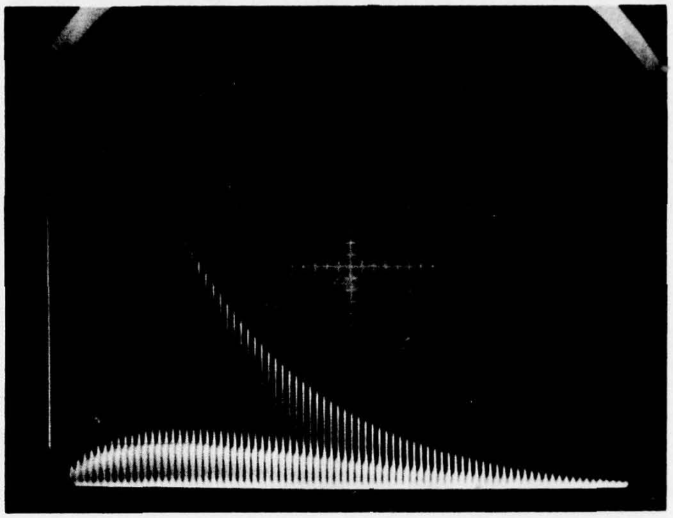

Figure 46. Time Domain Performance of Cascaded Modules in Feedback Loop. Center frequency of RF pulsed input is 830.8 MHz. Input pulse is highlighted (darker). Horizontal scale 200 μsec/div

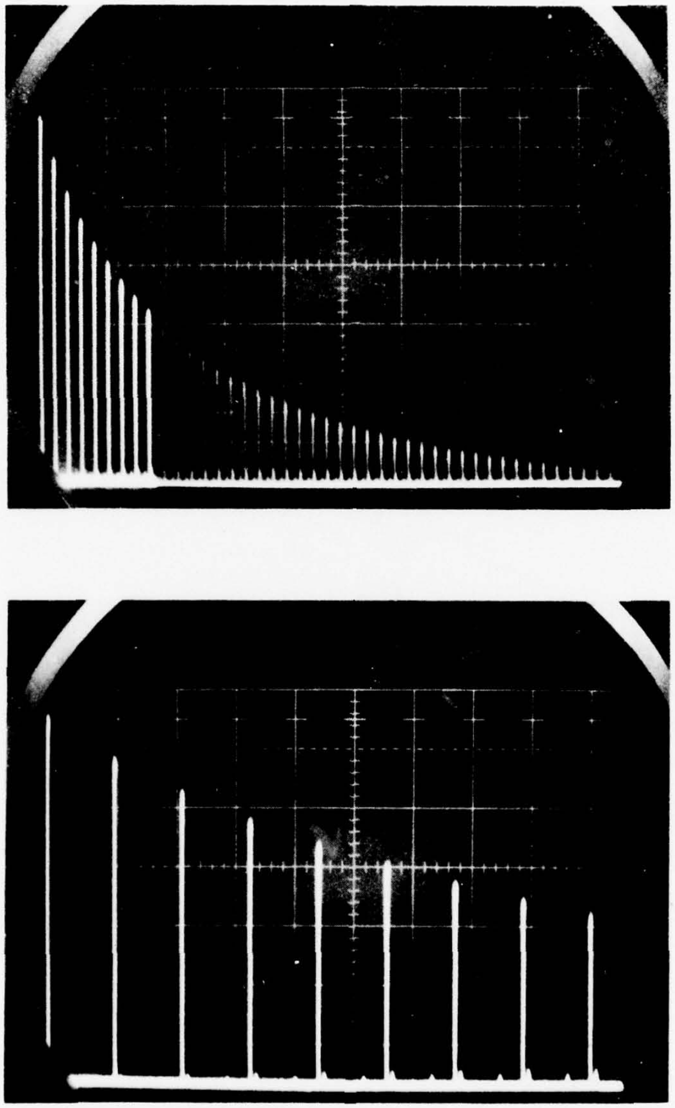

Figure 47. Time Domain Performance of Cascaded Modules in Feedback Loop. Center Frequency of RF Pulsed Input is 830.7 MHz. Top: 100 μsec/div with input pulse and first eight delayed pulses highlighted. Bottom: 20 μsec/div blowup of the nine highlighted pulses showing additional detail

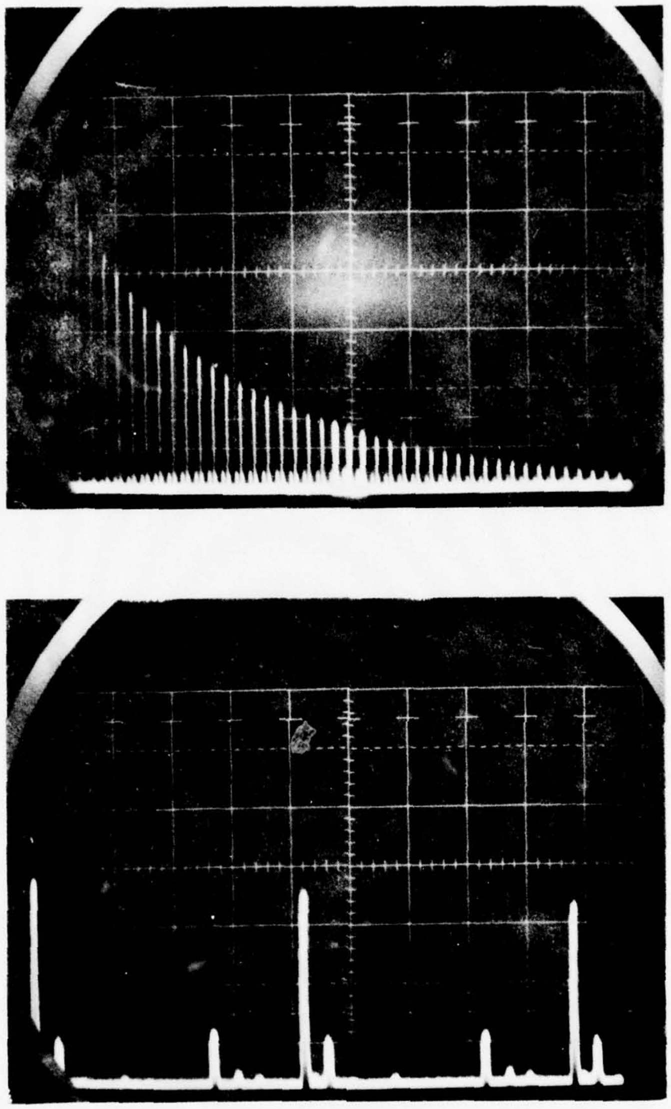

Figure 48. Time Domain Performance of Cascaded Modules in Feedback Loop. Center frequency of RF pulse 830.7 MHz. Top: 100 μsec/div with 21st to 23rd delayed pulses highlighted. Bottom: 5 μsec/div blowup of the three highlighted pulses showing additional detail. Scope gain also increased

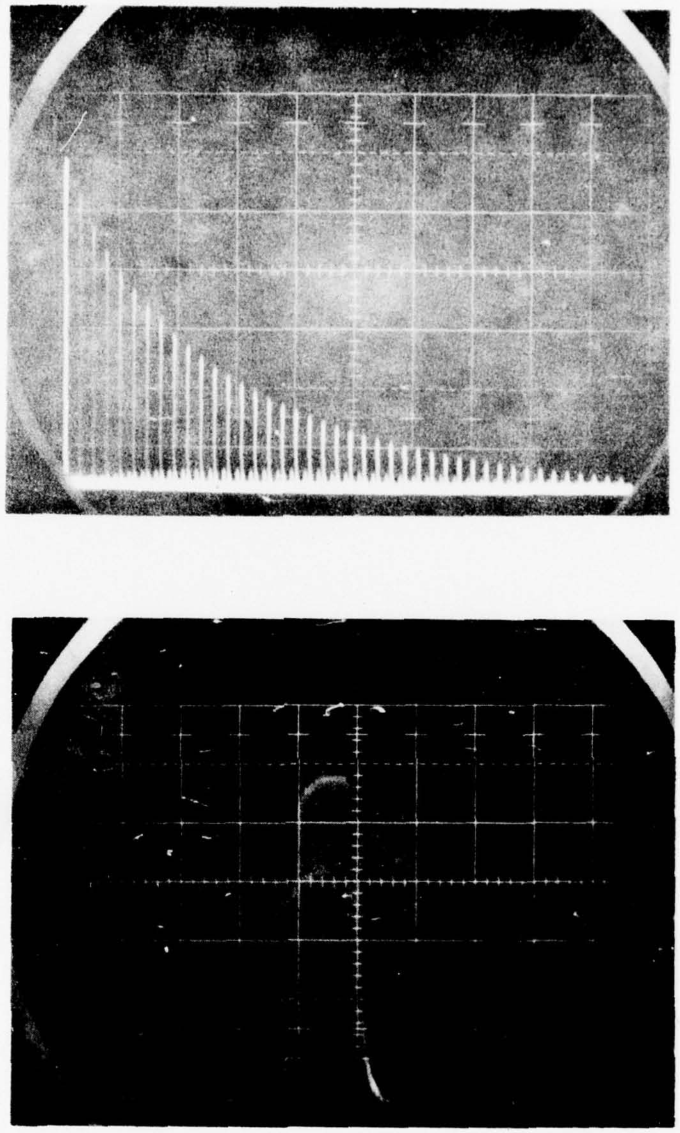

Figure 49. Time Domain Performance of Cascaded Modules in Feedback Loop. Center frequency of RF pulse 830.7 MHz. Top: 100 μsec/div with first delayed pulse highlighted. Bottom: 0.5 μsec/div blowup of the highlighted pulse showing additional detail

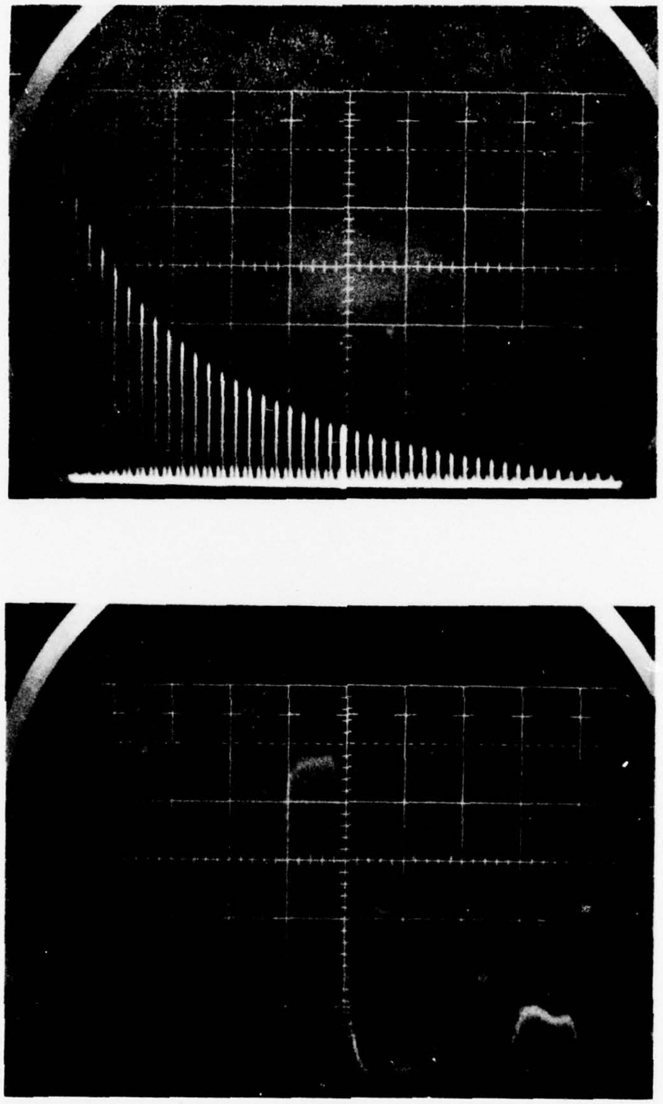

Figure 50. Time Domain Performance of Cascaded Modules in Feedback Loop. Center frequency of RF pulse 830.7 MHz. Top: 100 μsec/div with 22nd delayed pulse highlighted. Bottom: 0.5 μsec/div blowup of the highlighted pulse showing additional detail including spurious. Scope gain also increased

Insertion loss vs frequency characteristics for the 22nd delayed pulse (corresponding to a time delay of 498 μsec) are shown in Figure 51. As expected the slightly non-flat frequency response of the original 3 cascaded modules illustrated in Figure 43 is accentuated or magnified by the continuous recirculation. This would, of course, not occur in an actual case where all different delay modules would be used. However, simulation of the actual case certainly provides sufficient information to evaluate the delay module concept, and that was the intent. From the 13 dB ripple shown in Figure 51 and the 22 recirculations involved, it can be estimated that the three cascaded modules caused ~0.6 dB ripple on each pass; in good agreement with data obtained from Figure 43.

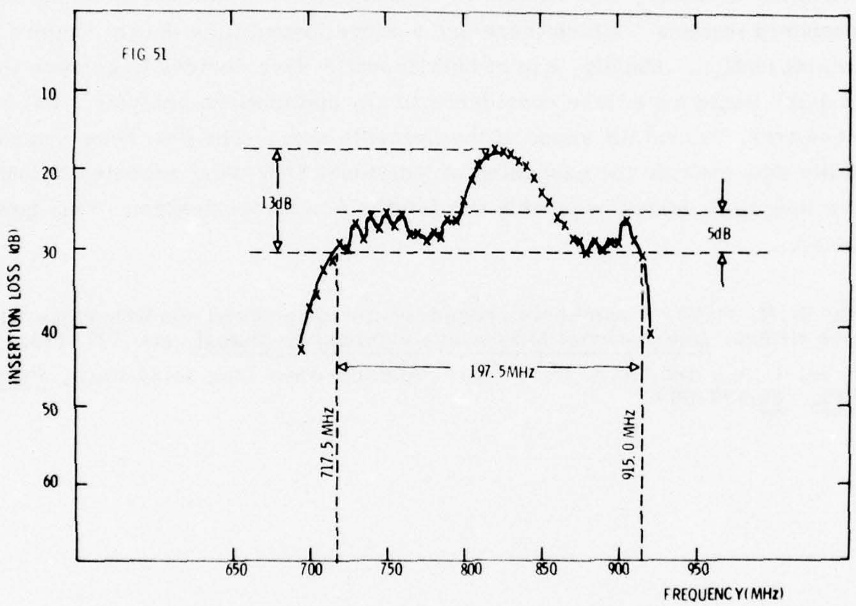

Figure 51. Insertion Loss vs Frequency After 498 μsec of Time Delay Using Cascaded Delay Modules With Feedback Loop

5. SUMMARY AND CONCLUSIONS

A technique for achieving low loss (in fact, up to 10 dB of gain has been achieved), ultra-flat frequency response, wide bandwidth, delay modules has been demonstrated. Each module consists of a SAW delay line, an equalizer, and an amplifier. Pass band flatness of up to 0.2 dB (± 0.1 dB) over 215 MHz centered at 800 MHz has been

achieved for a module having 7.5 μsec of time delay. Longer delay increments could be used in future designs due to the excess gain referenced above. Cascading three modules and using a feedback loop to simulate additional cascade elements has resulted in a linear 500 μsec delay system over a 200 MHz bandwidth. In this case since 22 recirculations through the same modules were required, bandpass ripple could not cancel resulting in an overall value of 13 dB.

Further use of this technique will depend on an analysis of its advantages and disadvantages when compared to alternate schemes in a given application. For example, although SAW delay line design and fabrication is quite simple and low passband ripple easily achievable in the present case as compared to designs incorporating a flat passband,[9, 10] an equalizer is required. Or again, use of a high center frequency allows a low percentage bandwidth to easily achieve a large absolute bandwidth. However, this results in high propagation loss when compared to lower frequency designs[10] which therefore achieve longer time delays, before requiring amplification. Finally, use of bulk acoustic wave devices to achieve the required delay would have to be considered in any applications analysis. All of this is, however, beyond the scope of the present paper. The goal here was to successfully demonstrate the cascading of individual SAW delay modules in order to achieve long time delays over wide bandwidths in a linear system. This goal was attained.

9. Smith, W.R. (1973) A synthesis procedure for unapodized nondispersive surface wave filters, International Microwave Symposium Digest, pp. 117-118.

10. Coldren, L.A., and Shaw, H.J. (1976) Surface-wave long delay lines, Proc. IEEE 64:598-609.

References

1. Slobodnik, A. J., Jr. (1973) UHF and Microwave Frequency Acoustic Surface Wave Delay Lines: Design, TR-73-0538, RADC/EEA, Hanscom AFB, Mass. 01731.

2. Slobodnik, A. J., Jr., and Conway, E. D. (1970) New high-frequency high-coupling low-beam steering cut for acoustic surface waves on $LiNbO_3$, Electron. Lett. 6:171-172.

3. Erlinger, W. G. (1973) Fine Grain Amplitude Equalization, TR-73-0162, Wavecom, Inc., 9036 Winnetka Ave., Northridge, CA 91324.

4. Armstrong, D. G. (1973) Research to Develop Microwave Acoustic Surface Wave Delay Lines.

5. Wolf, E. D., and Weglein, R. D. (1973) Microwave Acoustic Surface Wave Delay Lines, TR-73-0570, Hughes Research Laboratories, 3011 Malibu Canyon Road, Malibu, CA 90265.

6. Smith, H. I. (1976) Fabrication techniques for surface-acoustic-wave and thin film optical devices, Proc. IEEE 62:1361-3187.

7. Slobodnik, A. J., Jr., Fenstermacher, T. E., Kearns, W. J., Roberts, G. A., and Silva, J. H. (1975) A minimal diffraction lithium tantalate substrate for contiguous SAW Butterworth filters, IEEE Ultrasonics Sympsoium Proc., pp 405-407.

8. Sandy, F. (1976) User's Manual For Analysis of Interdigital Transducers For Acoustic Surface Wave Devices, Contract No. F19628-73-C-0277, Raytheon Research Division, Waltham, MA 02154.

9. Smith, W. R. (1973) A synthesis procedure for unapodized nondispersive surface wave filters, International Microwave Symposium Digest, pp. 117-118.

10. Coldren, L. A., and Shaw, H. J. (1976) Surface-wave long delay lines, Proc. IEEE 64:598-609.

Appendix A

Time Domain Spurious and Frequency Ripple

The purpose of this appendix is to investigate the effect of a spurious output time signal on the output frequency response.

Consider a desired output $y_D(t)$ and a spurious output occurring at a time, t_o, later

$$y_s(t) = Ry_D(t - t_o) \tag{A1}$$

where R is the relative scale factor between signals.

These time signals have the following frequency spectra

$$y_D(t) \Longleftrightarrow y_D(f) \tag{A2}$$

$$y_s(t) \Longleftrightarrow R\, e^{-j2\pi f t_o}\, y_D(f) \tag{A3}$$

and

$$y_{TOT}(t) \equiv y_D(t) + y_s(t) \Longleftrightarrow y_D(f)[1 + R\, e^{-j2\pi f t_o}] = y_{TOT}(f) \tag{A4}$$

y_{TOT} can be rewritten as

$$y_{TOT}(f) = y_D(f)\, [\, 1 + R \cos(-2\pi f t_o) + jR \sin(-2\pi f t_o)] \tag{A5}$$

or

$$y_{TOT}(f) = y_D(f) \left[1 + R \cos 2\pi f t_o - j R \sin 2\pi f t_o \right] . \tag{A6}$$

Thus

$$|y_{TOT}(f)| = y_D(f) \sqrt{(1 + R \cos 2\pi f t_o)^2 + (R \sin 2\pi f t_o)^2} \tag{A7}$$

where $y_D(f)$ has been assumed real.

Rewriting,

$$|y_{TOT}(f)| = y_D(f) \sqrt{1 + 2 R \cos 2\pi f t_o + R^2 (\cos^2 2\pi f t_o + \sin^2 2\pi f t_o)} \tag{A8}$$

or

$$|y_{TOT}(f)|^2 = y_D{}^2 \left[(1+R^2) + 2 R \cos 2\pi f t_o \right] . \tag{A9}$$

This function is sketched in Figure A1.

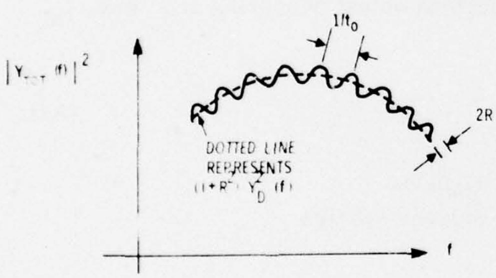

Figure A1. Illustration of Frequency Ripple Due to Time Spurious Signal

The ratio of the maximum to minimum signal is

$$\text{RATIO} = \frac{1+R^2+2R}{1+R^2-2R} = \frac{(1+R)\,(1+R)}{(1-R)\,(1-R)} = \left(\frac{1+R}{1-R} \right)^2 . \tag{A10}$$

Thus peak-to-peak ripple in dB is given by

$$\text{Ripple in dB} = 20 \log_{10} \left[\frac{1+R}{1-R} \right] . \tag{A11}$$

The relative time domain strength of the desired and spurious signals is most often given in dB (power). That is,

$$R_D(\mathrm{dB}) = 20 \log_{10} R \tag{A12}$$

or

$$R = e^{-\frac{R_D}{20}\ln 10} = e^{-0.1151293\, R_D} . \tag{A13}$$

Thus substituting Eq. (A13) into Eq. (A11) results in our final expression

$$\text{Ripple in dB} = 20 \log_{10} \left[\frac{1 + e^{-0.1151\, R_D}}{1 - e^{-0.1151\, R_D}} \right] \qquad \boxed{\begin{array}{c}\text{BASIC}\\\text{EQUATION}\end{array}} \tag{A14}$$

Appendix B

SAW Delay Line Master Specification

This appendix provides the detailed specifications used in ordering the SAW delay line interdigital transducer chrome masters. These details are as follows. (Note that the intermediate taps or inner transducers were not used for this report.)

All transducers are of the interdigital type. All line widths are to be 1.2 μm and spacings are to be 1.2 μm for center-to-center distances between adjacent fingers of 2.4 μm.

There are four transducers in each set and two sets. All of the transducers in a set must be parallel to each other to within 30 sec of arc.

The two outer (Type 0) transducers in each set are to have 6 lines or 3 pairs. The two inner (Type 1) transducers in each set are to have 3 lines or 1-1/2 pairs.

Chrome thickness is to be suitable for exposure of photo resist.

For other physical dimensions, see Figures B1 and B2.

The transducers are to be clear on a chrome field. For dimensions of the chrome field refer to Figures B1 and B2. IMPORTANT: The long edges of the chrome field are to be parallel to ± 1 min to the two transducer center lines and perpendicular to the short edges of the chrome field.

A clear reference mark is to extend along the overall center line between both sets of transducers a distance of approximately 3.5 mm into the chrome field. It is to be approximately 0.003 in. wide. The overall center line is to be perfectly parallel (± 1 min) to the two transducer center lines.

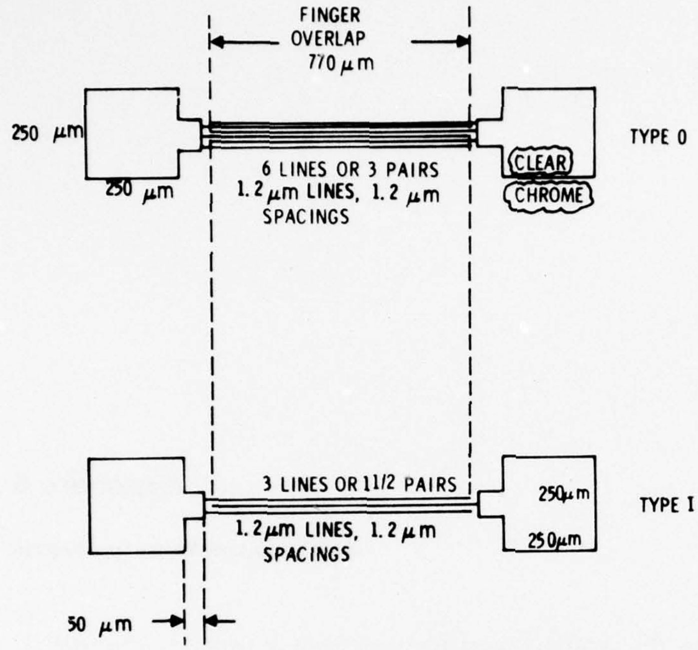

Figure B1. Closeup of Interdigital Transducers. Note that double electrodes are not used and that dummy electrodes are not used

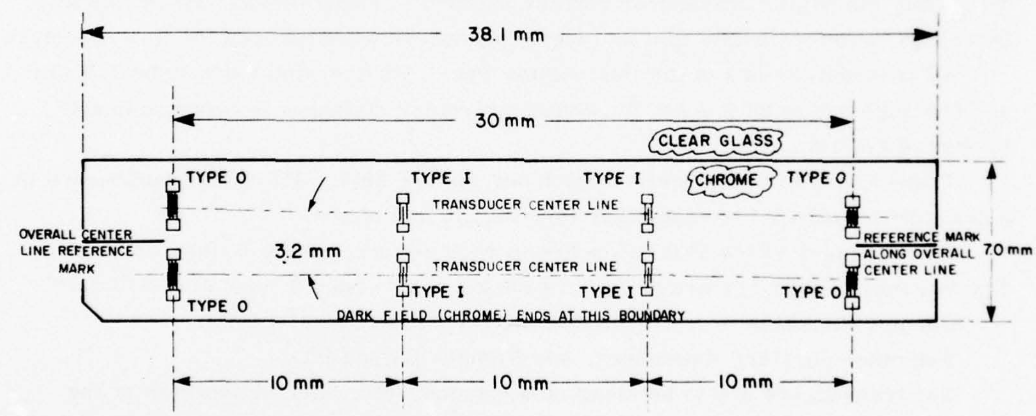

Figure B2. Overall View of Master (not necessarily to scale)

The following masters are to be supplied (on 2 in. × 2 in. glass slides).

Quantity: 2 Description: 0211 cover glass[6] 0.0075 to 0.0098 in.

Appendix C

Frequency Response Data and Curve Fitting Computer Program

This appendix provides the numerical frequency response data corresponding to delay line No. 11 in the form of a test case for the Curve Fitting Computer Program.* This is preceded by a listing of the program.

*Provided by T. Persakis and P. Tsipouras.

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          PROGRAM SLC        74/74    OPT=1                               FTN 4.5+414        12/10/76  0u.14.46

 1              PROGRAM SLO(INPUT,OUTPUT)
                DIMENSION PROGID(3)
         COMMENT.                                                       )05(Y,)05(X NOISNEMID
                DIMENSION X(99),Y(99)                                                  .TNEMMOC
 5              COMMON/LABEL/J
                DATA PROGID/9HSLOBODNIK,8H X3716  ,4HPLOT/
                CALL PLTID3(PROGID,900.0,11.0,1.0)
                CALL PLOT(1.0,1.0,-3)
         COMMENT.                                                             2,1=J 009 00
10              DO 900 J=1,3                                                           .TNEMMOC
         COMMENT.                                                             1,1=J 009 00
         COMMENT.                                                             5,1=J 009 00
         COMMENT.                                                             4,1=J 009 00
         COMMENT.                                                             6,1=J 009 00
15              READ 800, N,N1,NDN,N2,NPLT,NPTS
                READ 801,    (X(I),I=1,N)
                READ 801,    (Y(I),I=1,N)
                CALL LSTSQRS(X,Y,N,N1,NDN,N2,NPLT,NPTS)
            800 FORMAT(6I5)
20          801 FORMAT(8F10.3)
            900 CONTINUE
                IF(NPLT.NE.0) CALL ENDPLT
                STOP
                END


CARD NR. SEVERITY  DETAILS    DIAGNOSIS OF PROBLEM

   10       I                 CONTROL VARIABLE IN COMMON OR EQUIVALENCED, OPTIMIZATION MAY BE INHIBITED.
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SUBROUTINE LSTSQRS    74/74    OPT=1                        FTN 4.5+414        12/1./76  0..14.46

              SUBROUTINE LSTSQRS(X,Y,N,N1,NDN,N2,NPLT,NPTS)
        C     .............................................................. ...
        C     N IS THE NUMBER OF INPUT POINTS
        C     N1  =  THE DEGREE OF THE FIRST POLYNOMIAL TO BE FITTED
        C     NDN =  THE STEP THE DEGREE OF THE POLYNOMIALS INCREASE
        C     N2  =  THE DEGREE OF THE LAST  POLYNOMIAL TO BE FITTED
        C     NPLT EQ. ANY NON-ZERO INTEGER PLOTS ARE GENERATED
        C     NPLT = 0  NO PLOTS ARE GENERATED
        C     NPTS  IS THE NUMBER OF POINTS TO BE PLOTTED
        C     .............................................................. ...
        COMMENT.                                             )05(Y,)05(X NOISNEMID
              DIMENSION X(99),Y(99)                                      .TNEMMOC
              DIMENSION XAX(200)
              A1=X(1)
              A2=X(N)
              CALL NET(A1,A2,NPTS,XAX)
              NPTS=NPTS+1
              ND=N1
            3 CONTINUE
              CALL POLYFT (X,Y,N,ND,XAX,NPLT,NPTS)
              ND = ND+NDN
              IF (ND.LE.N2) GO TO 3
              RETURN
              END
```

```
SUBROUTINE NET        74/74    OPT=1                        FTN 4.5+414        12/10/76  0..14.46

              SUBROUTINE NET(A1,A2,N,X)
              DIMENSION X(200)
              H1=1.0
              SN=N
              H=(A2-A1)/SN
              NP1=N+1
              DO 100 I=1,NP1
              SI=I
              X(I)=A1+(SI-H1)*H
          100 CONTINUE
              RETURN
              END
```

```
      SUBROUTINE POLYFT (X,Y,N,ND,XAX,NPLT,NPTS)
      DIMENSION XAX(200),YAX(200)
COMMENT.    )05(SP,)024(A,)05(C,)05(SER,)05(HTOOMS,)05(Y,)05(X NOISNEMID
       DIMENSION X(99),Y(99),SMOOTH(99),RES(99),C(99),A(420),PS(99)     .TNEMMOC
      DIMENSION  SUMX(200),SMYX(101), AMEANX(101)
      DIMENSION F(3)
      COMMON/LABEL/W
      INTEGER W
C     ................................................................ ....
C     LEAST SQUARES POLYNOMIAL FIT     .................................
C     ND = DEGREE OF THE POLY. TO BE FITTED
C     NA = ND + 1, NUMBER OF COEFFICIENTS IN POLY.
C     CO    IS  THE  COEFFICIENT OF THE ZEROTH POWER  IN   THE  POLYNOMIAL
C     C     IS  THE  VECTOR  OF  COEFFICIENTS OF THE POLYNOMIAL  IN ASCENDING
C               POWERS , STARTING FROM C(1).
C     N  = NUMBER OF OBSERVATIONS,CONSIDERING%X,Y< AS ONE OBSERVATION.
C     SMOOTH IS THE COMPUTED VALUE OF Y = YC
C     ................................................................ ....

      H100=100.
      KOR = ND
      NA = KOR+1
      NN  =  N - NA
      AAA = FLOAT(NN)
      PTS= N                                                          POLY0070
      KTOR= 2*KOR                                                     POLY0090
C                                                                     POLY0040
C                                                                     POLY0100
C     INITIALIZATION                                                  POLY0110
      DO  1  I=1,KOR                                                  POLY0120
      SMYX(I)= 0.0                                                    POLY0130
    1 AMEANX(I)= 0.0                                                  POLY0140
      DO  2  I=1,KTOR                                                 POLY0150
    2 SUMX(I)= 0.0                                                    POLY0160
      SUMY= 0.0                                                       POLY0170
C     NORMALIZATION WITH RESPECT TO XMAX                              POLY0190
      XMAX= X(1)                                                      POLY0200
      DO  100  I=2,N                                                  POLY0210
      IF( X(I) -XMAX) 100,101,101                                     POLY0220
  101 XMAX= X(I)                                                      POLY0230
  100 CONTINUE                                                        POLY0240
      DO  102  I=1,N                                                  POLY0250
  102 X(I)= X(I)/XMAX                                                 POLY0260
C                                                                     POLY0270
C                                                                     POLY0280
C     FORMULATION OF NORMAL EQUATIONS                                 POLY0290
      DO  3 J=1,KTOR
      DO  3 I=1,N                                                     POLY0310
    3 SUMX(J)= SUMX(J) +X(I)**J                                       POLY0320
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```
      DO  4  I=1,N                                              POLY0330
    4 SUMY= SUMY+ Y(I)                                          POLY0340
      AMEANY= SUMY/PTS                                          POLY0350
      DO  6  J=1,KOR                                            POLY0360
      AMEANX(J)= SUMX (J)/PTS                                   POLY0370
      DO  6  I=1,N                                              POLY0380
    6 SMYX(J)= SMYX(J) +Y(I)*X(I)**J                            POLY0390
       DO 88 I = 1,KOR
      C(I)= SMYX(I) -PTS*AMEANX(I)*AMEANY                       POLY0410
      DO  8  J=1,KOR                                            POLY0420
      K= I+J                                                    POLY0430
      IJ =(J-1)*KOR +I                                          POLY0440
    8 A(IJ) =SUMX(K) -PTS* AMEANX(I)*AMEANX(J)                  POLY0450
       IJ1 = I
       IJ2 = (KOR - 1) * KOR  +  I
   88  CONTINUE
C                                                               POLY0460
C     CROUT@S  REDUCTION  METHOD                                POLY0470
      DO  11 I=2,KOR                                            POLY0480
      I1I=(I-1)*KOR + 1                                         POLY0490
   11 A(I1I) = A(I1I)/ A(1)                                     POLY0500
      DO  12 J=2,KOR                                            POLY0510
      KM= J-1                                                   POLY0520
      DO 14 I=J,KOR                                             POLY0530
      AP1= 0.0                                                  POLY0540
      DO114 K=1,KM                                              POLY0550
      IK =(K-1)* KOR+ I                                         POLY0560
      KJ =(J-1)* KOR+ K                                         POLY0570
  114 AP1 = AP1 + A(IK) *A(KJ)                                  POLY0580
      IJ =(J-1)* KOR+ I                                         POLY0590
   14 A(IJ) = A(IJ) -AP1                                        POLY0600
      JP= J+1                                                   POLY0610
      IF (JP- KOR) 444, 444, 445                                POLY0620
  444 DO 16 I=JP,KOR                                            POLY0630
      AP1= 0.0                                                  POLY0640
      DO116 K=1,KM                                              POLY0650
      JK =(K-1)* KOR + J                                        POLY0660
      KI =(I-1)* KOR + K                                        POLY0670
  116 AP1 =AP1 +A(JK) *A(KI)                                    POLY0680
      JI =(I-1)* KOR + J                                        POLY0690
      JJ =(J-1)* KOR + J                                        POLY0700
   16 A(JI) = (A(JI) -AP1)/A(JJ)                                POLY0710
  445 DUMMY= 0.0                                                POLY0720
   12 CONTINUE                                                  POLY0730
      C(1) =C(1)/A(1)                                           POLY0740
      IF(KOR.EQ.1) GO TO 123
      DO  18 I=2,KOR                                            POLY0750
      AP1= 0.0                                                  POLY0760
      IM=I-1                                                    POLY0770
      DO 118 K=1,IM                                             POLY0780
      IK =(K-1)* KOR + I                                        POLY0790
  118 AP1=AP1 +A(IK) *C(K)                                      POLY0800
      II =(I-1)* KOR + I                                        POLY0810
   18 C(I) =(C(I)- AP1) / A(II)                                 POLY0820
      KORM= KOR-1                                               POLY0830
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```
      IF (KORM) 122, 123,122                                            POLY0840
  122 DO  21 I=1,KORM                                                   POLY0850
      AP1= 0.0                                                          POLY0860
      M= KOR-I                                                          POLY0870
      MP= M+1                                                           POLY0880
      DO 121 K=MP,KOR                                                   POLY0890
      MK =(K-1)* KOR +M                                                 POLY0900
  121 AP1 =AP1 + A(MK)* C(K)                                            POLY0910
   21 C(M) =C(M) -AP1                                                   POLY0920
   23 AP1= 0.0                                                          POLY0930
      DO 24  I=1,KOR                                                    POLY0940
   24 AP1 =AP1 +AMEANX(I) *C(I)                                         POLY0950
      CO  = AMEANY -AP1                                                 POLY0960
C                                                                       POLY0970
  778 SRES = 0.0                                                        POLY1030
      DO  77 I=1,N                                                      POLY1070
       SMOOTH(I) = CO
      DO  27 J=1,KOR                                                    POLY1090
 27    SMOOTH(I) = SMOOTH(I) + C(J)*X(I)**J
       RES(I) = Y(I) - SMOOTH(I)
      SRES= SRES +RES(I)**2
C                                                                       POLY1130
      X(I)= X(I)*XMAX                                                   POLY1150
      IF(Y(I).NE.0.0) GO TO 76
      IF(Y(I).EQ.0.0) PS(I)=0.0
      GO TO 77
 76   PS(I) = H100*RES(I)/Y(I)
  77    CONTINUE
      SUM1 = SRES
      SUM = SRES
      STDERR = SRES/PTS
       STDV =  SQRT (SRES/PTS)
      DO 28 I=1,KOR                                                     POLY1210
   28 C(I)   =C(I)   /XMAX**I                                           POLY1220
      VAR=0.0
      DO 29 I=1,N
      CALL PLNML(CO,C,ND,X(I),POLY)
      SVAR=POLY-Y(I)
      VAR=VAR+SVAR**2
   29 CONTINUE
      ND = KOR
      PRINT 90
   90 FORMAT(1H1,/)
      PRINT 912,ND
      PRINT 921
      PRINT 922,    (I,X(I),Y(I),SMOOTH(I),RES(I),PS(I),I=1,N)
      PRINT 923
      PRINT 944,    CO,(C(J),J=1,ND)
   78 PRINT 926
   79 PRINT 924,    SRES, STDERR,STDV
```

```
  912 FORMAT(8X,23HPOLYNOMIAL FIT - DEGREE,2X,I2,/)
  921 FORMAT ( //15X,15HX ( IND. VAR. )10X,15HY ( DEP. VAR. )8X,17HYC (
     1COMPUTED Y ),7X,19HRESIDUAL ( Y - YC ), 9X,13H100*(Y-YC)/Y ,//)
  922 FORMAT ( I5,3E25.8,2E24.8)
  923 FORMAT (//13X,38HPOLYNOMIAL COEFF.(IN ASCENDING POWERS)//)
  924 FORMAT ( 3E40.8)
  926 FORMAT (//13X,32HSUM OF SQUARES OF RESIDUALS=SRES,23X,10HSRES/N
     1 ,29X,12HSQRT(SRES/N),//)
  944 FORMAT ( E30.8)
C     ..................................................................
      DO 80 I=1,NPTS
      XXX=XAX(I)
      CALL PLNML(CO,C,ND,XXX,POLY)
      YAX(I)=POLY
   80 CONTINUE
      PRINT 8112
 8112 FORMAT(1H0,////45X,1HX,19X,1HY)
      PRINT 8113,   (XAX(I),YAX(I),I=1,NPTS)
 8113 FORMAT(1X,32X,2E20.7)
      IF(NPLT.EQ.0) RETURN
      CALL SCALE(X,10.,N,1,10.,XMIN,DX)
      CALL SCALE(Y,8.0,N,1,10.,YMIN,DY)
      CALL AXIS(0.0,0.0,15HFREQUENCY (MHZ),-15,   10.,0.0,XMIN,DX,10.0)
      CALL AXIS(0.0,0.0,28HRELATIVE INSERTION LOSS (DB),28,8.0,90.0,YMIN
     1,DY,10.0)
      CALL LINE(X,Y,N,1,-1,11,XMIN,DX,YMIN,DY,.12)
      CALL LINE(XAX,YAX,NPTS,1,0,0,XMIN,DX,YMIN,DY,.12)
      CALL SYMBOL(0.5,2.0,0.20,9HDEGREE   ,0.0,9)
      FP=ND
      CALL NUMBER(2.0,2.0,.2,FP,0.0,-1)
      PRINT 2800
 2800 FORMAT(1H0,//)

      IF(ND.EQ.1) GO TO 4500
      IF(ND.EQ.2) GO TO 3000
      IF(ND.EQ.3) GO TO 3500
      IF(ND.EQ.4) GO TO 4000
      IF(ND.EQ.4) GO TO 4000
 3000 CONTINUE
      ARITH=C(1)
      PARAN=2.0*C(2)
      R1=-(ARITH/PARAN)
      X1=X(1)
      X2=X(N)
      IF((R1.LT.X1).AND.(R1.GT.X2)) GO TO 3002
       WIND=CO+C(1)*R1+C(2)*R1*R1
      PRINT 30,R1,WIND
 3002 CONTINUE
      GO TO 5000
```

```
 3500 CONTINUE
C      FIRST DERIVATIVE OF THE CUBIC POLYNOMIAL
      D0=3.0*C(3)
      D1=2.0*C(2)
      D2=C(1)
      CALL QDRTC(D0,D1,D2,R1,R2,NR)
      X1=X(1)
      X2=X(N)
      PRINT 10,NR
   10 FORMAT(1X,5HNR = ,I2)
      IF(NR.EQ.0) RETURN
      IF(NR.EQ.2) GO TO 40
      PRINT 20,R1
   20 FORMAT(5X,5HR1 = ,F10.2)
      IF((R1.LT.X1).AND.(R1.GT.X2)) RETURN
      WIND=C(3)*R1**3+C(2)*R1*R1+C(1)*R1+CO
      PRINT 30,  R1,WIND
   30 FORMAT(40X,6HANSWER,5X,4HZ = ,F10.2,5X,7HF(Z) = ,F10.3)
      GO TO 5000
   40 CONTINUE
      PRINT 20,R1
      PRINT 45,R2
   45 FORMAT(5X,5HR2 = ,F10.3)
      IF((R1.GE.X1).AND.(R1.LE.X2)) GO TO 70
      IF((R2.GE.X1).AND.(R2.LE.X2)) GO TO 60
      GO TO 5000
   60 CONTINUE
      R1=R2
   70 CONTINUE
      WIND=C(3)*R1**3+C(2)*R1*R1+C(1)*R1+CO
      PRINT 95,  R1,WIND
   95 FORMAT(40X,6HANSWER,5X,4HZ = ,F10.2,5X,7HF(Z) = ,F10.3)
      GO TO 5000

 4000 CONTINUE
C     FIRST DERIVATIVE OF THE 4TH DEGREE POLYNOMIAL
      F(3)=4.0*C(4)
      F(2)=3.0*C(3)
      F(1)=2.0*C(2)
      FO=C(1)
      BNDLOW=X(1)
      BNDUP=X(N)
      STEP=0.01
      N=3
      ERROR=0.0000001
      CALL PLYRT1(BNDLOW,BNDUP,RT,N,FO,F,ERROR,STEP)
      X1=X(1)
      X2=X(N)
      S1=RT
```

```
      IF((S1.LT.X1).AND.(S1.GT.X2)) GO TO 290
      R1=S1
      WIND=C(4)*R1**4+C(3)*R1**3+C(2)*R1*R1+C(1)*R1+CO
      PRINT 95,R1,WIND
      GO TO 5000
  290 CONTINUE
      E=F(3)
      B=F(2)+F(3)*S1
      D=-F0/S1
      CALL QDRTC(E,B,D,R1,R2,NR)
      PRINT 10,NR
      IF(NR.EQ.0) RETURN
      IF(NR.EQ.2) GO TO 300
      PRINT 20,R1
      IF((R1.LT.X1).AND.(R1.GT.X2)) RETURN
      WIND=C(4)*R1**4+C(3)*R1**3+C(2)*R1*R1+C(1)*R1+CO
      PRINT 30,  R1,WIND
      GO TO 5000
  300 CONTINUE
      PRINT 20,R1
      PRINT 45,R2
      IF((R1.GE.X1).AND.(R1.LE.X2)) GO TO 350
      IF((R2.GE.X1).AND.(R2.LE.X2)) GO TO 330
      GO TO 5000
  330 CONTINUE
      R1=R2
  350 CONTINUE
      WIND=C(4)*R1**4+C(3)*R1**3+C(2)*R1*R1+C(1)*R1+CO
      PRINT 95,  R1,WIND
      GO TO 5000
 4500 CONTINUE
      R1=-CO/C(1)
      WIND=C(1)*R1+CO
      PRINT 95,R1,WIND
 5000 CONTINUE
C***********************
      S=(R1-XMIN)/DX
      T=(WIND-YMIN)/DY
      CALL SYMBOL(S,T,0.12,5,0.0,-1)
      CALL SYMBOL(0.5,1.5,0.20,5HZ    =,0.0,5)
      CALL SYMBOL(0.5,1.0,0.20,5HF(Z)=,0.0,5)
      IF(W.EQ.1)
     1CALL SYMBOL(0.5,0.5,0.20,40HDELAY LINE 11
     2  ,0.0,40)
      IF(W.EQ.2)
     1CALL SYMBOL(0.5,0.5,0.20,40HDELAY LINE 12
     2  ,0.0,40)
      IF(W.EQ.3)
     1CALL SYMBOL(0.5,0.5,0.20,40HDELAY LINE 13
     2  ,0.0,40)
      CALL NUMBER(1.5,1.5,0.20,R1,0.0,3)
      CALL NUMBER(1.5,1.0,0.20,WIND,0.0,3)
C*******************************************
      CALL PLOT(14.0,0.0,-3)
C*******************************************
      RETURN                                                            POLY1270
      END                                                               POLY1280
```

```
SUBROUTINE QDRTC       74/74    OPT=1                        FTN 4.5+414         12/10/76  00.14.46

              SUBROUTINE QDRTC(A,B,C,R1,R2,NR)
              D=B*B-4.0*A*C
              IF(A.EQ.0.0) GO TO 40
              IF(D)10,20,30
        10    CONTINUE
              NR=0
              RETURN
        20    CONTINUE
              X=-B/(2.0*A)
              NR=1
              R1=X
              GO TO 100
        30    CONTINUE
              NR=2
              SQD=SQRT(D)
              X1=(-B+SQD)/(2.0*A)
              X2=(-B-SQD)/(2.0*A)
              R1=AMIN1(X1,X2)
              R2=AMAX1(X1,X2)
              GO TO 100
        40    CONTINUE
              NR=1
              R1=-C/B
       100    CONTINUE
              RETURN
              END
```

```
      SUBROUTINE PLYRT1(BNDLOW,BNDUP,RT,N,A0,A,ERROR,DISTNS)
      DIMENSION A(100)
      PRINT 50,N
   50 FORMAT(1H0,27X,26H ORDER OF THE POLYNOMIAL =,I3//)
      PRINT 60,A0
   60 FORMAT(30X,36H ARRAY OF COEFFICIENTS IS AS FOLLOWS//,49X,5H A0 =,
     1    E16.6)
      PRINT 65,  (I,A(I),I=1,N)
   65 FORMAT(46X,3H A(,I2,3H) =,E16.6)
      PRINT 70,  BNDLOW,BNDUP
   70 FORMAT(//31X,23H LOWER BOUND OF ROOTS =,E14.6//,31X,
     1 23H UPPER BOUND OF ROOTS =,E14.6//)
      PRINT 75,ERROR
   75 FORMAT(40X,14H ERROR        =,E14.6//)
      PRINT 77,DISTNS
   77 FORMAT(21X,33H MINIMUM DISTANCE BETWEEN ROOTS =,E14.6//)
      PRINT 79
   79 FORMAT(20X,37H MAXIMUM DESIRED NUMBER OF ROOTS =  1//)
      H0=0.0
      IROOT=0
      H01= 0.1
      H1=DISTNS
   80 DX1=BNDLOW
      IROOT=IROOT+1
      DX=H1
      DX2=BNDUP
      DL2    = H0
      X = DX1
      X2=DX1
  100 CONTINUE
      X1=X2
      DL1 = DL2
  200 CALL PLNML (A0,A,N,X,POLY)
C     PRINT 885,X,POLY
      X2=X
      DL2 = POLY
      IF( ABS(POLY).LT.ERROR) GO TO 420
      IF (DL1*DL2.LT.H0) GO TO 300
      X    =  X + DX
      IF(X2.GT.(DX2+DX)) GO TO 500
      IF(X2.LE.(DX2+DX)) GO TO 100
  300 CONTINUE
      IF ( ABS(X2-X1).LT.ERROR) GO TO 400
      IF(X2.GT.(DX2+DX)) GO TO 500
      X    =  X - DX
      DX   =  DX*H01
      X    = X + DX
      DL2 = DL1
      X2=X1
```

```
      GO TO 100
  400 CONTINUE
      ROOT = X1-DL1*(X2-X1)/(DL2-DL1)
      GO TO 423
  420 ROOT=X
  423 CONTINUE
      CALL PLNML (A0,A,N,ROOT,POLY)
      PRINT 422,  IROOT,ROOT,POLY
  422 FORMAT(21X,6HROOT (,I3,5H ) = ,E16.6,20X,19H POLYNOMIAL VALUE =,
     1E16.6)
      IF(IROOT.EQ.1) RT=ROOT
      RETURN
  424 CALL PLNML (A0,A,N,ROOT,POLY)
      GO TO 80
  500 CONTINUE
      PRINT 301,X2
  301 FORMAT(20X,15H X2.GT.(DX2+DX),E16.6//)
C 885 FORMAT (1H ,2E20.5)
C*****IN PLYRT1 ONE REAL ROOT IS FOUND.
C*****BNDLOW IS THE LOWER BOUND, BNDUP IS THE UPPER BOUND OF THE ROOTS.
C*****N IS THE DEGREE OF THE POLYNOMIAL.
C*****A0 IS THE CONSTANT TERM OF THE POLYNOMIAL.
C*****A IS THE ARRAY OF COEFFICIENTS SUCH THAT A(I) IS THE COEFFICIENT
C*****OF X**I, FOR I=1 TO N
C*****ERROR IS THE MAXIMUM ERROR DESIRED.
C*****IF THE VALUE OF POLY IS LESS THAN ERROR, A ROOT IS FOUND.
C*****IF THE ABSOLUTE VALUE OF %X2-X1) IS LESS THAN ERROR, A ROOT IS FOUND.
      RETURN
      END
```

SUBROUTINE PLNML 74/74 OPT=1 FTN 4.5+414 12/10/76 00.14.46

```
      SUBROUTINE  PLNML (A0,A,N,X,POLY)
C     ................................... HORNERS RULE FOR POLYNOMIAL ...........
C*****PLNML CALCULATES POLY, THE VALUE OF THE POLYNOMIAL WITH THE
C*****GIVEN VALUE OF X.
      DIMENSION A(100),B(100)
      B(N+1) = 0.
      DO 100 I=1,N
      J=N-I+1
      B(J) = A(J) + X*B(J+1)
  100 CONTINUE
      POLY = A0 + X*B(1)
      RETURN
      END
```

POLYNOMIAL FIT - DEGREE 2

	X (IND. VAR.)	Y (DEP. VAR.)	YC (COMPUTED Y)	RESIDUAL (Y - YC)	100*(Y-YC)/Y
1	.70000000E+03	.21000000E+00	.24741674E+00	-.37416740E-01	-.17817495E+02
2	.70500000E+03	-.80000000E-01	-.23744222E-01	-.56255778E-01	.70319723E+02
3	.71000000E+03	-.37000000E+00	-.28270555E+00	-.87294450E-01	.23593094E+02
4	.71500000E+03	-.62000000E+00	-.52946725E+00	-.90532753E-01	.14602057E+02
5	.72000000E+03	-.80000000E+00	-.76402931E+00	-.35970690E-01	.44963363E+01
6	.72500000E+03	-.10100000E+01	-.98639174E+00	-.23608260E-01	.23374514E+01
7	.73000000E+03	-.12400000E+01	-.11965545E+01	-.43445462E-01	.35036663E+01
8	.73500000E+03	-.14400000E+01	-.13945177E+01	-.45482297E-01	.31584926E+01
9	.74000000E+03	-.16100000E+01	-.15802812E+01	-.29718764E-01	.18458860E+01
10	.74500000E+03	-.17600000E+01	-.17538451E+01	-.61548648E-02	.34971823E+00
11	.75000000E+03	-.19000000E+01	-.19152094E+01	.15209402E-01	-.80049484E+00
12	.75500000E+03	-.20200000E+01	-.20643740E+01	.44374036E-01	-.21967345E+01
13	.76000000E+03	-.21500000E+01	-.22013390E+01	.51339037E-01	-.23875622E+01
14	.76500000E+03	-.22400000E+01	-.23261044E+01	.86104406E-01	-.38439467E+01
15	.77000000E+03	-.23400000E+01	-.24386701E+01	.98670142E-01	-.42166727E+01
16	.77500000E+03	-.24200000E+01	-.25390362E+01	.11903624E+00	-.49188531E+01
17	.78000000E+03	-.25000000E+01	-.26272027E+01	.12720271E+00	-.50881086E+01
18	.78500000E+03	-.26000000E+01	-.27031696E+01	.10316955E+00	-.39681597E+01
19	.79000000E+03	-.26600000E+01	-.27669368E+01	.10693676E+00	-.40201788E+01
20	.79500000E+03	-.27200000E+01	-.28185043E+01	.98504329E-01	-.36214827E+01
21	.80000000E+03	-.27800000E+01	-.28578723E+01	.77872269E-01	-.28011607E+01
22	.80500000E+03	-.28100000E+01	-.28850406E+01	.75040575E-01	-.26704831E+01
23	.81000000E+03	-.27800000E+01	-.29000092E+01	.12000925E+00	-.43168795E+01
24	.81500000E+03	-.28100000E+01	-.29027783E+01	.92778290E-01	-.33017185E+01
25	.82000000E+03	-.28500000E+01	-.28933477E+01	.43347698E-01	-.15209719E+01
26	.82500000E+03	-.28500000E+01	-.28717175E+01	.21717474E-01	-.76201662E+00
27	.83000000E+03	-.28400000E+01	-.28378876E+01	-.21123837E-02	.74379708E-01
28	.83500000E+03	-.28300000E+01	-.27918581E+01	-.38141874E-01	.13477694E+01
29	.84000000E+03	-.27800000E+01	-.27336290E+01	-.46370996E-01	.16680215E+01
30	.84500000E+03	-.27400000E+01	-.26632002E+01	-.76799752E-01	.28029107E+01
31	.85000000E+03	-.26500000E+01	-.25805719E+01	-.69428140E-01	.26199298E+01
32	.85500000E+03	-.25900000E+01	-.24857438E+01	-.10425616E+00	.40253344E+01
33	.86000000E+03	-.25100000E+01	-.23787162E+01	-.13128382E+00	.52304309E+01
34	.86500000E+03	-.23800000E+01	-.22594889E+01	-.12051110E+00	.50634917E+01
35	.87000000E+03	-.22500000E+01	-.21280620E+01	-.12193802E+00	.54194676E+01
36	.87500000E+03	-.21400000E+01	-.19844354E+01	-.15556457E+00	.72693726E+01
37	.88000000E+03	-.19900000E+01	-.18286092E+01	-.16139076E+00	.81101883E+01
38	.88500000E+03	-.18400000E+01	-.16605834E+01	-.17941658E+00	.97509008E+01
39	.89000000E+03	-.16600000E+01	-.14803580E+01	-.17964203E+00	.10821809E+02
40	.89500000E+03	-.14200000E+01	-.12879329E+01	-.13206711E+00	.93005006E+01
41	.90000000E+03	-.11900000E+01	-.10833082E+01	-.10669182E+00	.89656995E+01
42	.90500000E+03	-.90000000E+00	-.86648383E+00	-.33516173E-01	.37240192E+01
43	.91000000E+03	-.58000000E+00	-.63745985E+00	.57459846E-01	-.99068699E+01
44	.91500000E+03	-.24000000E+00	-.39623623E+00	.15623623E+00	-.65098430E+02
45	.92000000E+03	.11000000E+00	-.14281298E+00	.25281298E+00	.22982999E+03
46	.92500000E+03	.49000000E+00	.12280989E+00	.36719011E+00	.74936756E+02

POLYNOMIAL COEFF.(IN ASCENDING POWERS)

.15862033E+03
-.39704187E+00
.24399266E-03

SUM OF SQUARES OF RESIDUALS=SRES	SRES/N	SQRT(SRES/N)
.59122016E+00	.12852612E-01	.11336936E+00

X	Y
.7000000E+03	.2474167E+00
.7022500E+03	.1238846E+00
.7045000E+03	.2822891E-02
.7067500E+03	-.1157684E+00
.7090000E+03	-.2318893E+00
.7112500E+03	-.3455397E+00
.7135000E+03	-.4567197E+00
.7157500E+03	-.5654293E+00
.7180000E+03	-.6716684E+00
.7202500E+03	-.7754372E+00
.7225000E+03	-.8767355E+00
.7247500E+03	-.9755634E+00
.7270000E+03	-.1071921E+01
.7292500E+03	-.1165808E+01
.7315000E+03	-.1257224E+01
.7337500E+03	-.1346171E+01
.7360000E+03	-.1432646E+01
.7382500E+03	-.1516652E+01
.7405000E+03	-.1598187E+01
.7427500E+03	-.1677251E+01
.7450000E+03	-.1753845E+01
.7472500E+03	-.1827969E+01
.7495000E+03	-.1899622E+01
.7517500E+03	-.1968805E+01
.7540000E+03	-.2035517E+01
.7562500E+03	-.2099759E+01
.7585000E+03	-.2161531E+01
.7607500E+03	-.2220832E+01
.7630000E+03	-.2277662E+01
.7652500E+03	-.2332022E+01
.7675000E+03	-.2383912E+01
.7697500E+03	-.2433332E+01
.7720000E+03	-.2480281E+01
.7742500E+03	-.2524759E+01
.7765000E+03	-.2566767E+01

.7787500E+03	-.2606305E+01
.7810000E+03	-.2643372E+01
.7832500E+03	-.2677969E+01
.7855000E+03	-.2710095E+01
.7877500E+03	-.2739751E+01
.7900000E+03	-.2766937E+01
.7922500E+03	-.2791652E+01
.7945000E+03	-.2813897E+01
.7967500E+03	-.2833671E+01
.7990000E+03	-.2850975E+01
.8012500E+03	-.2865808E+01
.8035000E+03	-.2878171E+01
.8057500E+03	-.2888064E+01
.8080000E+03	-.2895486E+01
.8102500E+03	-.2900437E+01
.8125000E+03	-.2902919E+01
.8147500E+03	-.2902930E+01
.8170000E+03	-.2900470E+01
.8192500E+03	-.2895540E+01
.8215000E+03	-.2888140E+01
.8237500E+03	-.2878269E+01
.8260000E+03	-.2865927E+01
.8282500E+03	-.2851116E+01
.8305000E+03	-.2833834E+01
.8327500E+03	-.2814081E+01
.8350000E+03	-.2791858E+01
.8372500E+03	-.2767165E+01
.8395000E+03	-.2740001E+01
.8417500E+03	-.2710367E+01
.8440000E+03	-.2678262E+01
.8462500E+03	-.2643687E+01
.8485000E+03	-.2606641E+01
.8507500E+03	-.2567125E+01
.8530000E+03	-.2525139E+01
.8552500E+03	-.2480682E+01
.8575000E+03	-.2433755E+01
.8597500E+03	-.2384357E+01
.8620000E+03	-.2332489E+01
.8642500E+03	-.2278151E+01
.8665000E+03	-.2221342E+01
.8687500E+03	-.2162062E+01
.8710000E+03	-.2100313E+01
.8732500E+03	-.2036092E+01
.8755000E+03	-.1969402E+01
.8777500E+03	-.1900241E+01
.8800000E+03	-.1828609E+01
.8822500E+03	-.1754507E+01
.8845000E+03	-.1677935E+01
.8867500E+03	-.1598892E+01
.8890000E+03	-.1517379E+01
.8912500E+03	-.1433395E+01
.8935000E+03	-.1346941E+01
.8957500E+03	-.1258017E+01

.8980000E+03	-.1166622E+01
.9002500E+03	-.1072757E+01
.9025000E+03	-.9764210E+00
.9047500E+03	-.8776148E+00
.9070000E+03	-.7763382E+00
.9092500E+03	-.6725912E+00
.9115000E+03	-.5663737E+00
.9137500E+03	-.4576859E+00
.9160000E+03	-.3465275E+00
.9182500E+03	-.2328988E+00
.9205000E+03	-.1167997E+00
.9227500E+03	.1769895E-02
.9250000E+03	.1228099E+00

ANSWER Z = 813.63 F(Z) = -2.903

POLYNOMIAL FIT - DEGREE 3

	X (IND. VAR.)	Y (DEP. VAR.)	YC (COMPUTED Y)	RESIDUAL (Y - YC)	100*(Y-YC)/Y
1	.70000000E+03	.21000000E+00	.42727103E-01	.16727290E+00	.79653760E+02
2	.70500000E+03	-.80000000E-01	-.17384995E+00	.93849954E-01	-.11731244E+03
3	.71000000E+03	-.37000000E+00	-.38443009E+00	.14430095E-01	-.39000256E+01
4	.71500000E+03	-.62000000E+00	-.58872482E+00	-.31275179E-01	.50443837E+01
5	.72000000E+03	-.80000000E+00	-.78644563E+00	-.13554366E-01	.16942957E+01
6	.72500000E+03	-.10100000E+01	-.97730404E+00	-.32695964E-01	.32372242E+01
7	.73000000E+03	-.12400000E+01	-.11610115E+01	-.78988473E-01	.63700381E+01
8	.73500000E+03	-.14400000E+01	-.13372796E+01	-.10272039E+00	.71333604E+01
9	.74000000E+03	-.16100000E+01	-.15058198E+01	-.10418021E+00	.64708207E+01
10	.74500000E+03	-.17600000E+01	-.16663436E+01	-.93656443E-01	.53213888E+01
11	.75000000E+03	-.19000000E+01	-.18185624E+01	-.81437576E-01	.42861882E+01
12	.75500000E+03	-.20200000E+01	-.19621879E+01	-.57812112E-01	.28619857E+01
13	.76000000E+03	-.21500000E+01	-.20969315E+01	-.53068548E-01	.24683046E+01
14	.76500000E+03	-.22400000E+01	-.22225046E+01	-.17495383E-01	.78104389E+00
15	.77000000E+03	-.23400000E+01	-.23386189E+01	-.13811161E-02	.59022055E-01
16	.77500000E+03	-.24200000E+01	-.24449858E+01	.24985755E-01	-.10324692E+01
17	.78000000E+03	-.25000000E+01	-.25413167E+01	.41316732E-01	-.16526693E+01
18	.78500000E+03	-.26000000E+01	-.26273233E+01	.27323315E-01	-.10508967E+01
19	.79000000E+03	-.26600000E+01	-.27027170E+01	.42717008E-01	-.16059025E+01
20	.79500000E+03	-.27200000E+01	-.27672093E+01	.47209310E-01	-.17356364E+01
21	.80000000E+03	-.27800000E+01	-.28205117E+01	.40511725E-01	-.14572563E+01
22	.80500000E+03	-.28100000E+01	-.28623358E+01	.52335752E-01	-.18624823E+01
23	.81000000E+03	-.27800000E+01	-.28923929E+01	.11239289E+00	-.40429099E+01

24	.81500000E+03	-.28100000E+01	-.29103947E+01	.10039465E+00	-.35727635E+01
25	.82000000E+03	-.28500000E+01	-.29160525E+01	.66052530E-01	-.23172326E+01
26	.82500000E+03	-.28500000E+01	-.29090780E+01	.59078027E-01	-.20729132E+01
27	.83000000E+03	-.28400000E+01	-.28891826E+01	.49182644E-01	-.17317832E+01
28	.83500000E+03	-.28300000E+01	-.28560779E+01	.26077884E-01	-.92148000E+00
29	.84000000E+03	-.27800000E+01	-.28094752E+01	.29475248E-01	-.10602607E+01
30	.84500000E+03	-.27400000E+01	-.27490862E+01	.90862384E-02	-.33161454E+00
31	.85000000E+03	-.26500000E+01	-.26746224E+01	.24622356E-01	-.92914550E+00
32	.85500000E+03	-.25900000E+01	-.25857951E+01	-.42048981E-02	.16235128E+00
33	.86000000E+03	-.25100000E+01	-.24823160E+01	-.27684021E-01	.11029491E+01
34	.86500000E+03	-.23800000E+01	-.23638965E+01	-.16103513E-01	.67661819E+00
35	.87000000E+03	-.22500000E+01	-.22302481E+01	-.19751871E-01	.87786092E+00
36	.87500000E+03	-.21400000E+01	-.20810824E+01	-.58917594E-01	.27531586E+01
37	.88000000E+03	-.19900000E+01	-.19161108E+01	-.73889180E-01	.37130241E+01
38	.88500000E+03	-.18400000E+01	-.17350449E+01	-.10495513E+00	.57040830E+01
39	.89000000E+03	-.16600000E+01	-.15375961E+01	-.12240394E+00	.73737311E+01
40	.89500000E+03	-.14200000E+01	-.13234759E+01	-.96524103E-01	.67974720E+01
41	.90000000E+03	-.11900000E+01	-.10923959E+01	-.97604127E-01	.82020275E+01
42	.90500000E+03	-.90000000E+00	-.84406749E+00	-.55932506E-01	.6214 229E+01
43	.91000000E+03	-.58000000E+00	-.57820226E+00	-.17977399E-02	.30995515E+00
44	.91500000E+03	-.24000000E+00	-.29451167E+00	.54511674E-01	-.22713198E+02
45	.92000000E+03	.11000000E+00	.72927629E-02	.10270724E+00	.93370216E+02
46	.92500000E+03	.49000000E+00	.32749955E+00	.16250045E+00	.33163357E+02

POLYNOMIAL COEFF.(IN ASCENDING POWERS)

-.45227624E+02
.36172538E+00
-.69362729E-03
.38466459E-06

SUM OF SQUARES OF RESIDUALS=SRES	SRES/N	SQRT(SRES/N)
.23373863E+00	.50812746E-02	.71283060E-01

X	Y
.70000000E+03	.4272710E-01
.70225000E+03	-.5545625E-01
.70450000E+03	-.1524573E+00
.70675000E+03	-.2482499E+00
.70900000E+03	-.3428077E+00
.71125000E+03	-.4361043E+00
.71350000E+03	-.5281135E+00
.71575000E+03	-.6188091E+00
.71800000E+03	-.7081646E+00

.7202500E+03	-.7961539E+00
.7225000E+03	-.8827507E+00
.7247500E+03	-.9679286E+00
.7270000E+03	-.1051661E+01
.7292500E+03	-.1133923E+01
.7315000E+03	-.1214685E+01
.7337500E+03	-.1293926E+01
.7360000E+03	-.1371615E+01
.7382500E+03	-.1447728E+01
.7405000E+03	-.1522238E+01
.7427500E+03	-.1595118E+01
.7450000E+03	-.1666344E+01
.7472500E+03	-.1735887E+01
.7495000E+03	-.1803722E+01
.7517500E+03	-.1869824E+01
.7540000E+03	-.1934164E+01
.7562500E+03	-.1996713E+01
.7585000E+03	-.2057458E+01
.7607500E+03	-.2116359E+01
.7630000E+03	-.2173394E+01
.7652500E+03	-.2228537E+01
.7675000E+03	-.2281762E+01
.7697500E+03	-.2333042E+01
.7720000E+03	-.2382351E+01
.7742500E+03	-.2429663E+01
.7765000E+03	-.2474952E+01
.7787500E+03	-.2518191E+01
.7810000E+03	-.2559353E+01
.7832500E+03	-.2598413E+01
.7855000E+03	-.2635345E+01
.7877500E+03	-.2670122E+01
.7900000E+03	-.2702717E+01
.7922500E+03	-.2733105E+01
.7945000E+03	-.2761259E+01
.7967500E+03	-.2787153E+01
.7990000E+03	-.2810760E+01
.8012500E+03	-.2832055E+01
.8035000E+03	-.2851011E+01
.8057500E+03	-.2867602E+01
.8080000E+03	-.2881801E+01
.8102500E+03	-.2893582E+01
.8125000E+03	-.2902919E+01
.8147500E+03	-.2909785E+01
.8170000E+03	-.2914155E+01
.8192500E+03	-.2916012E+01
.8215000E+03	-.2915300E+01
.8237500E+03	-.2912022E+01
.8260000E+03	-.2906142E+01
.8282500E+03	-.2897634E+01
.8305000E+03	-.2886471E+01
.8327500E+03	-.2872628E+01
.8350000E+03	-.2856078E+01
.8372500E+03	-.2836794E+01

.8395000E+03	-.2814751E+01
.8417500E+03	-.2789922E+01
.8440000E+03	-.2762281E+01
.8462500E+03	-.2731801E+01
.8485000E+03	-.2698457E+01
.8507500E+03	-.2662221E+01
.8530000E+03	-.2623068E+01
.8552500E+03	-.2580972E+01
.8575000E+03	-.2535905E+01
.8597500E+03	-.2487842E+01
.8620000E+03	-.2436757E+01
.8642500E+03	-.2382623E+01
.8665000E+03	-.2325414E+01
.8687500E+03	-.2265104E+01
.8710000E+03	-.2201666E+01
.8732500E+03	-.2135074E+01
.8755000E+03	-.2065301E+01
.8777500E+03	-.1992322E+01
.8800000E+03	-.1916111E+01
.8822500E+03	-.1836640E+01
.8845000E+03	-.1753884E+01
.8867500E+03	-.1667816E+01
.8890000E+03	-.1578410E+01
.8912500E+03	-.1485640E+01
.8935000E+03	-.1389480E+01
.8957500E+03	-.1289902E+01
.8980000E+03	-.1186882E+01
.9002500E+03	-.1080392E+01
.9025000E+03	-.9704058E+00
.9047500E+03	-.8568980E+00
.9070000E+03	-.7398420E+00
.9092500E+03	-.6192114E+00
.9115000E+03	-.4949799E+00
.9137500E+03	-.3671212E+00
.9160000E+03	-.2356091E+00
.9182500E+03	-.1004173E+00
.9205000E+03	.3848058E-01
.9227500E+03	.1811108E+00
.9250000E+03	.3274995E+00

NR = 2
R1 = 382.38
R2 = 819.758

ANSWER Z = 819.76 F(Z) = -2.916

POLYNCMIAL FIT - DEGPEE 4

	X (IND. VAR.)	Y (DEP. VAR.)	YC (COMPUTED Y)	RESIDUAL (Y - YC)	100*(Y-YC)/Y
1	.70000000E+03	.21000000E+00	.20886980E+00	.11301967E-02	.53818888E+00
2	.70500000E+03	-.80000000E-01	-.81549014E-01	.15490142E-02	-.19362677E+01
3	.71000000E+03	-.37000000E+00	-.35086685E+00	-.19133154E-01	.51711226E+01
4	.71500000E+03	-.62000000E+00	-.60043440E+00	-.19565599E-01	.31557417E+01
5	.72000000E+03	-.80000000E+00	-.83152433E+00	.31524330E-01	-.39405413E+01
6	.72500000E+03	-.10100000E+01	-.10453312E+01	.35331225E-01	-.34981411E+01
7	.73000000E+03	-.12400000E+01	-.12429716E+01	.29716226E-02	-.2396[illegible]698E+00
8	.73500000E+03	-.14400000E+01	-.14254840E+01	-.14516001E-01	.1008[illegible]556E+01
9	.74000000E+03	-.16100000E+01	-.15938288E+01	-.16171224E-01	.10044238E+01
10	.74500000E+03	-.17600000E+01	-.17488883E+01	-.11111685E-01	.63134575E+00
11	.75000000E+03	-.19000000E+01	-.18914669E+01	-.85330796E-02	.4491[illegible]946E+00
12	.75500000E+03	-.20200000E+01	-.20222908E+01	.22908399E-02	-.1134[illegible]792E+00
13	.76000000E+03	-.21500000E+01	-.21420083E+01	-.79917373E-02	.3717[illegible]871E+00
14	.76500000E+03	-.22400000E+01	-.22511893E+01	.11189321E-01	-.49952325E+00
15	.77000000E+03	-.23400000E+01	-.23503251E+01	.10326088E-01	-.44126581E+00
16	.77500000E+03	-.24200000E+01	-.24398326E+01	.19832581E-01	-.81952813E+00
17	.78000000E+03	-.25000000E+01	-.25200448E+01	.20044758E-01	-.80179033E+00
18	.78500000E+03	-.26000000E+01	-.25912205E+01	-.87794789E-02	.33767227E+00
19	.79000000E+03	-.26600000E+01	-.26535397E+01	-.64602869E-02	.24286793E+00
20	.79500000E+03	-.27200000E+01	-.27071041E+01	-.12895880E-01	.47411324E+00
21	.80000000E+03	-.27800000E+01	-.27519375E+01	-.28062530E-01	.10094435E+01
22	.80500000E+03	-.28100000E+01	-.27879854E+01	-.22014567E-01	.78343654E+00
23	.81000000E+03	-.27800000E+01	-.28151156E+01	.35115623E-01	-.12631519E+01
24	.81500000E+03	-.28100000E+01	-.28331176E+01	.23117594E-01	-.82269019E+00
25	.82000000E+03	-.28500000E+01	-.28417028E+01	-.82971552E-02	.29112825E+00
26	.82500000E+03	-.28500000E+01	-.28405048E+01	-.94951859E-02	.33316442E+00
27	.83000000E+03	-.28400000E+01	-.28290789E+01	-.10921115E-01	.3845[illegible]631E+00
28	.83500000E+03	-.28300000E+01	-.28069024E+01	-.23097619E-01	.81617029E+00
29	.84000000E+03	-.27800000E+01	-.27733746E+01	-.66254303E-02	.23832483E+00
30	.84500000E+03	-.27400000E+01	-.27278167E+01	-.12183340E-01	.4446[illegible]743E+00
31	.85000000E+03	-.26500000E+01	-.26694718E+01	.19471805E-01	-.73478508E+00
32	.85500000E+03	-.25900000E+01	-.25975051E+01	.75050960E-02	-.2897[illegible]205E+00
33	.86000000E+03	-.25100000E+01	-.25110036E+01	.10035710E-02	-.39982910E-01
34	.86500000E+03	-.23800000E+01	-.24089762E+01	.28976208E-01	-.12174877E+01
35	.87000000E+03	-.22500000E+01	-.22903539E+01	.40353929E-01	-.17935079E+01
36	.87500000E+03	-.21400000E+01	-.21539896E+01	.13989596E-01	-.65371943E+00
37	.88000000E+03	-.19900000E+01	-.19986580E+01	.86580148E-02	-.43507612E+00
38	.88500000E+03	-.18400000E+01	-.18230559E+01	-.16944066E-01	.92087316E+00
39	.89000000E+03	-.16600000E+01	-.16258020E+01	-.34197957E-01	.20601179E+01
40	.89500000E+03	-.14200000E+01	-.14054370E+01	-.14563024E-01	.10255651E+01
41	.90000000E+03	-.11900000E+01	-.11604233E+01	-.29576694E-01	.24854364E+01
42	.90500000E+03	-.90000000E+00	-.88914555E+00	-.10854448E-01	.12[illegible]6[illegible]498E+01
43	.91000000E+03	-.58000000E+00	-.58991017E+00	.99101733E-02	-.17086506E+01
44	.91500000E+03	-.24000000E+00	-.26094557E+00	.20945571E-01	-.87273214E+01
45	.92000000E+03	.11000000E+00	.39597909E-01	.10402091E-01	.94564462E+01
46	.92500000E+03	.49000000E+00	.49364798E+00	-.36479814E-02	-.74446600E+00

POLYNOMIAL COEFF.(IN ASCENDING POWERS)

.21838526E+04
-.10707490E+02
.19859591E-01
-.16527823E-04
.52038439E-08

SUM OF SQUARES OF RESIDUALS=SRES	SRES/N	SQRT(SRES/N)
.15591886E-01	.33895404E-03	.18410705E-01

X	Y
.7000000E+03	.2088698E+00
.7022500E+03	.7548055E-01
.7045000E+03	-.5347964E-01
.7067500E+03	-.1781397E+00
.7090000E+03	-.2986254E+00
.7112500E+03	-.4150593E+00
.7135000E+03	-.5275607E+00
.7157500E+03	-.6362458E+00
.7180000E+03	-.7412275E+00
.7202500E+03	-.8426155E+00
.7225000E+03	-.9405165E+00
.7247500E+03	-.1035034E+01
.7270000E+03	-.1126267E+01
.7292500E+03	-.1214314E+01
.7315000E+03	-.1299269E+01
.7337500E+03	-.1381220E+01
.7360000E+03	-.1460257E+01
.7382500E+03	-.1536453E+01
.7405000E+03	-.1609919E+01
.7427500E+03	-.1680702E+01
.7450000E+03	-.1748888E+01
.7472500E+03	-.1814548E+01
.7495000E+03	-.1877749E+01
.7517500E+03	-.1938558E+01
.7540000E+03	-.1997034E+01
.7562500E+03	-.2053238E+01
.7585000E+03	-.2107224E+01
.7607500E+03	-.2159044E+01
.7630000E+03	-.2208743E+01
.7652500E+03	-.2256381E+01
.7675000E+03	-.2301985E+01
.7697500E+03	-.2345601E+01
.7720000E+03	-.2387264E+01

.7742500E+03	-.2427006E+01
.7765000E+03	-.2464859E+01
.7787500E+03	-.2500848E+01
.7810000E+03	-.2534996E+01
.7832500E+03	-.2567324E+01
.7855000E+03	-.2597849E+01
.7877500E+03	-.2626584E+01
.7900000E+03	-.2653540E+01
.7922500E+03	-.2678724E+01
.7945000E+03	-.2702140E+01
.7967500E+03	-.2723790E+01
.7990000E+03	-.2743671E+01
.8012500E+03	-.2761777E+01
.8035000E+03	-.277810[illegible]E+01
.8057500E+03	-.2792628E+01
.8080000E+03	-.2805345E+01
.8102500E+03	-.2816235E+01
.8125000E+03	-.2825274E+01
.8147500E+03	-.2832438E+01
.8170000E+03	-.2837700E+01
.8192500E+03	-.2841[illegible]29E+01
.8215000E+03	-.2842389E+01
.8237500E+03	-.2841744E+01
.8260000E+03	-.2839053E+01
.8282500E+03	-.2834272E+01
.8305000E+03	-.2827354E+01
.8327500E+03	-.2818249E+01
.8350000E+03	-.2806902E+01
.8372500E+03	-.2793258E+01
.8395000E+03	-.2777257E+01
.8417500E+03	-.2758835E+01
.8440000E+03	-.2737926E+01
.8462500E+03	-.2714461E+01
.8485000E+03	-.2688366E+01
.8507500E+03	-.2659567E+01
.8530000E+03	-.2627983E+01
.8552500E+03	-.2593533E+01
.8575000E+03	-.2556131E+01
.8597500E+03	-.2515689E+01
.8620000E+03	-.2472114E+01
.8642500E+03	-.2425311E+01
.8665000E+03	-.2375183E+01
.8687500E+03	-.2321627E+01
.8710000E+03	-.2264539E+01
.8732500E+03	-.2203810E+01
.8755000E+03	-.2139331E+01
.8777500E+03	-.2070986E+01
.8800000E+03	-.1998655E+01
.8822500E+03	-.1922226E+01
.8845000E+03	-.1841567E+01
.8867500E+03	-.1756553E+01
.8890000E+03	-.1667054E+01
.8912500E+03	-.1572936E+01

.8935000E+03	-.1474063E+01
.8957500E+03	-.1370295E+01
.8980000E+03	-.1261488E+01
.9002500E+03	-.1147497E+01
.9025000E+03	-.1028171E+01
.9047500E+03	-.9033590E+00
.9070000E+03	-.7729038E+00
.9092500E+03	-.6366465E+00
.9115000E+03	-.4944250E+00
.9137500E+03	-.3460737E+00
.9160000E+03	-.1914237E+00
.9182500E+03	-.3030336E-01
.9205000E+03	.1374626E+00
.9227500E+03	.3120526E+00
.9250000E+03	.4936480E+00

ORDER OF THE POLYNOMIAL = 3

ARRAY OF COEFFICIENTS IS AS FOLLOWS

A0 = -.107075E+02
A(1) = .397192E-01
A(2) = -.495835E-04
A(3) = .208154E-07

LOWER BOUND OF ROOTS = .700000E+03

UPPER BOUND OF ROOTS = .925000E+03

ERROR = .100000E-06

MINIMUM DISTANCE BETWEEN ROOTS = .100000E-01

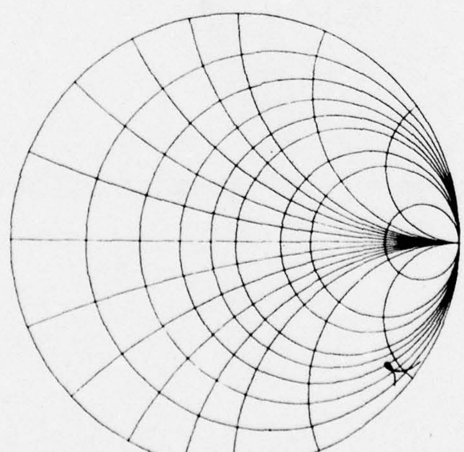
MAXIMUM DESIRED NUMBER OF ROOTS = 1

ROOT (1) = .821908E+03 POLYNOMIAL VALUE = -.273436E-07
ANSWER Z = 821.91 F(Z) = -2.842

Appendix D

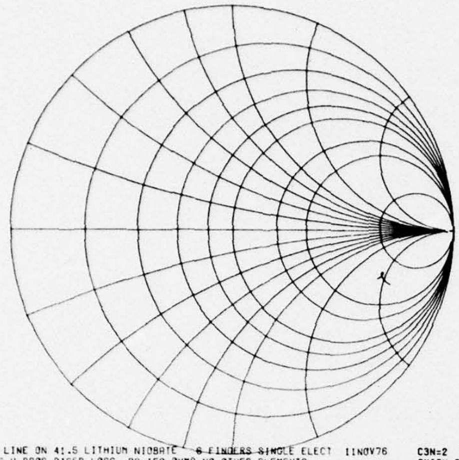
Parasitic Element Determination

This appendix includes theoretical Smith Chart impedance plots corresponding to the equivalent circuit model of the interdigital transducer used for the delay lines of this report. Various values of parasitic elements are investigated in order that a theoretical-experimental comparison can be made in the text.



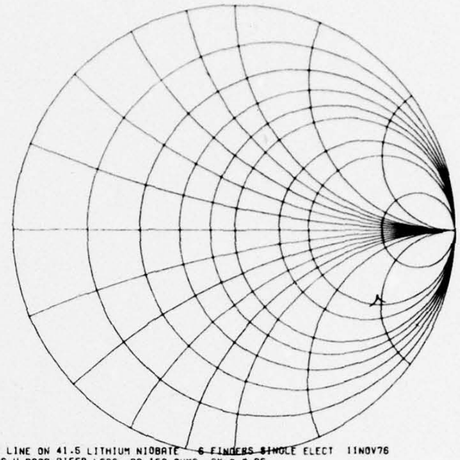
COMB 2

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 1NOV76
SMITH CHART FREQS WITH PROP-DIFFRACTION LOSS NO TUNING.NO PARASITICS



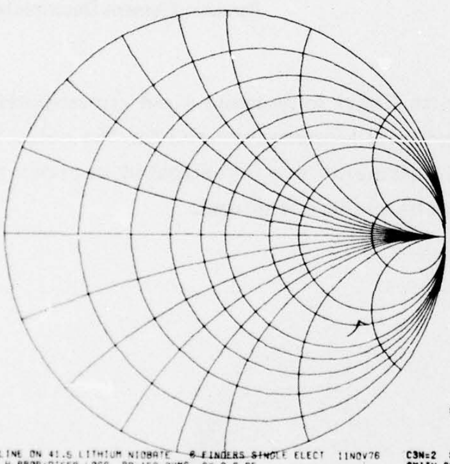
COMB 2

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=150 OHMS NO OTHER ELEMENTS



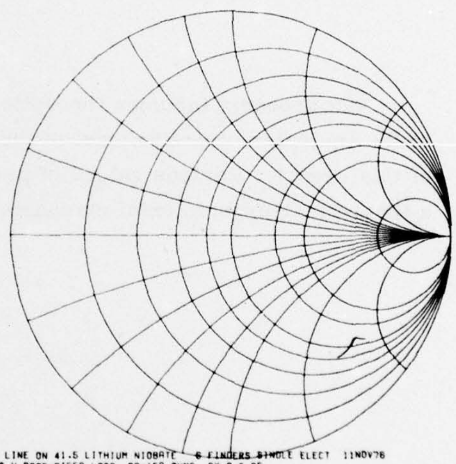
COMB 2

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=150 OHMS CX=0.3 PF



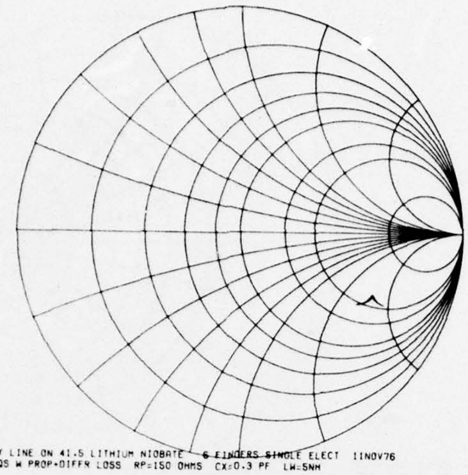
COMB 2

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=150 OHMS CX=0.6 PF



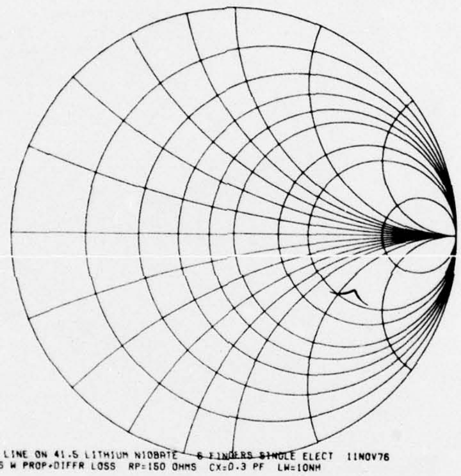
COMB 2

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=150 OHMS CX=0.9 PF



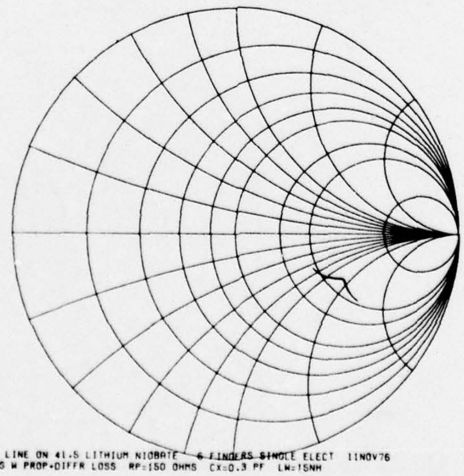
COMB 2

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=150 OHMS CX=0.3 PF LW=5NH



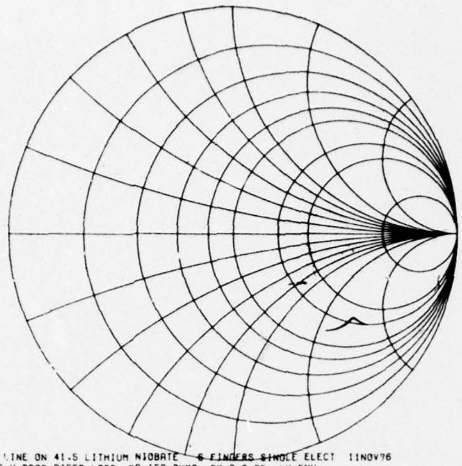
COMB 1

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=150 OHMS CX=0.3 PF LW=10NH



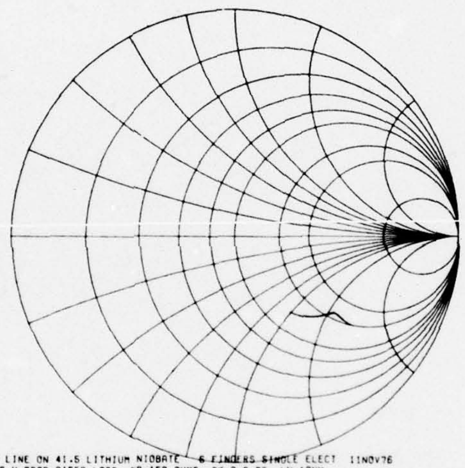
COMB 1

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=150 OHMS CX=0.3 PF LW=15NH



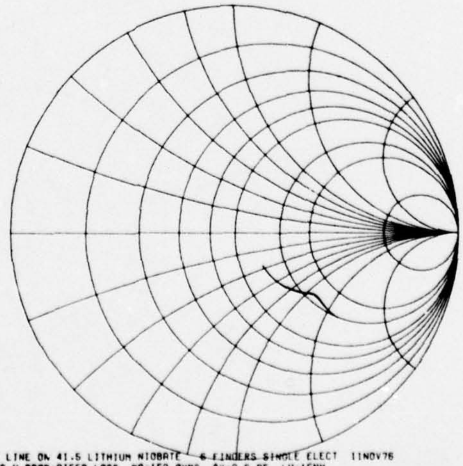
COMB 2

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=150 OHMS CX=0.6 PF LW=5NH



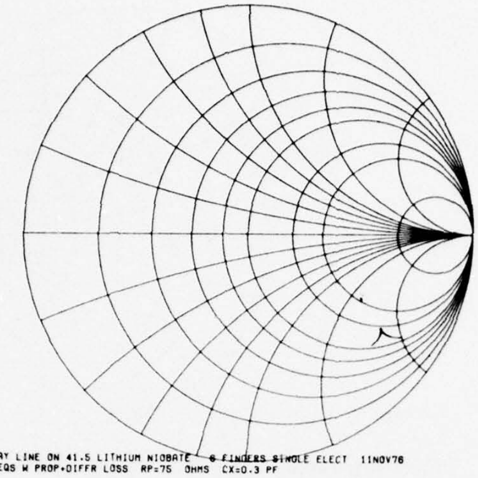
COMB 1

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=150 OHMS CX=0.6 PF LW=10NH



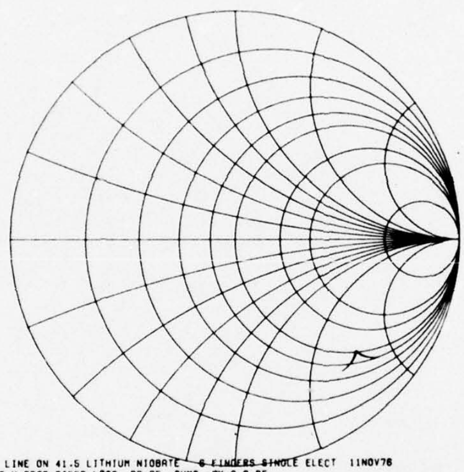
COMB 1

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=150 OHMS CX=0.6 PF LW=15NH



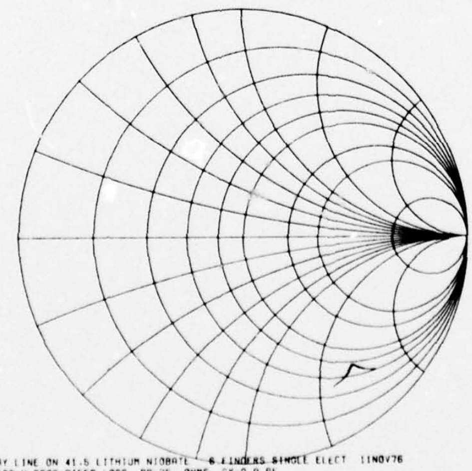
COMB 2

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=75 OHMS CX=0.3 PF



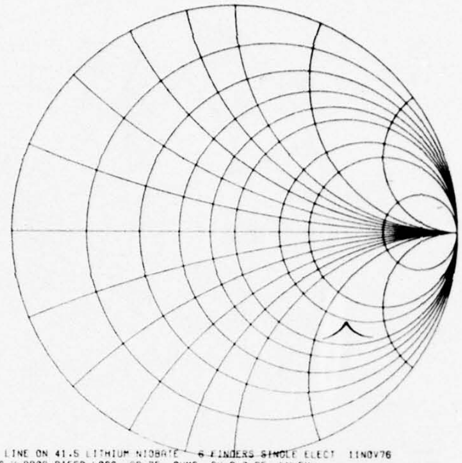
COMB 2

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=75 OHMS CX=0.6 PF



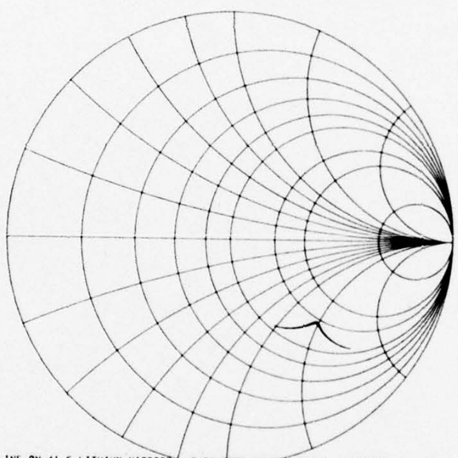
COMB 2

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=75 OHMS CX=0.9 PF



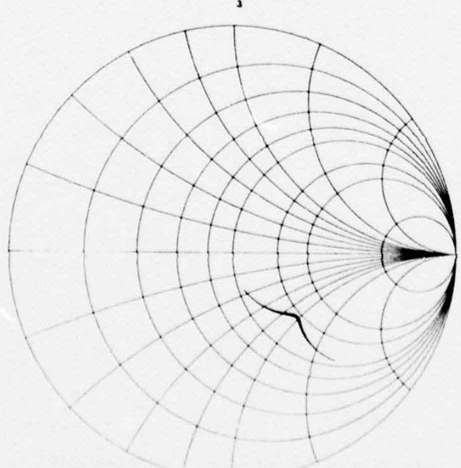
COMB 2

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=75 OHMS CX=0.3 PF LW=5NH



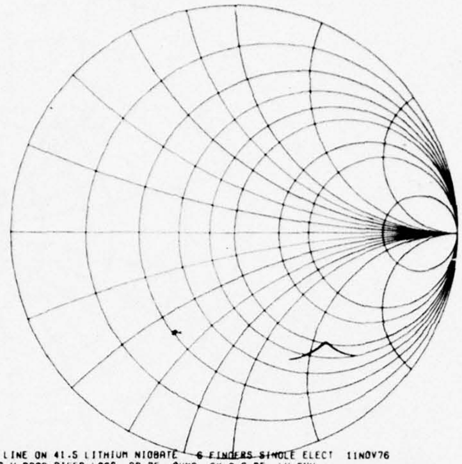
COMB 2

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=75 OHMS CX=0.3 PF LW=10NH



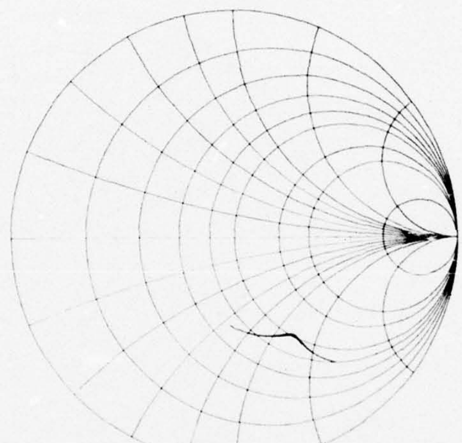
COMB 2

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=75 OHMS CX=0.3 PF LW=15NH



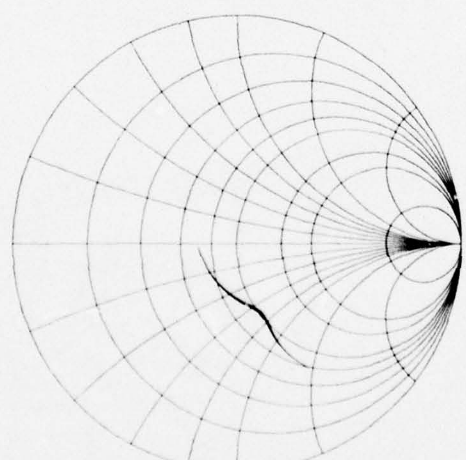
COMB 1

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=75 OHMS CX=0.6 PF LW=5NH



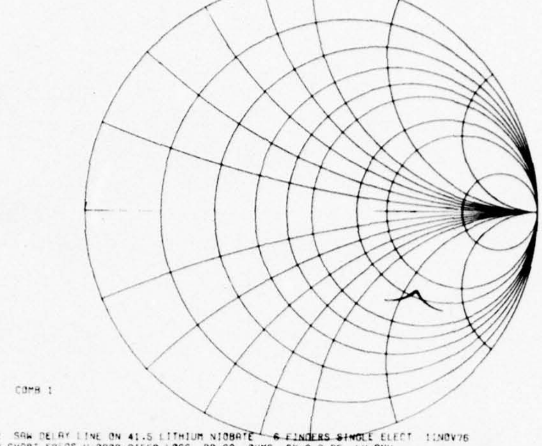
COMB 1

C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=75 OHMS CX=0.6 PF LW=10NH

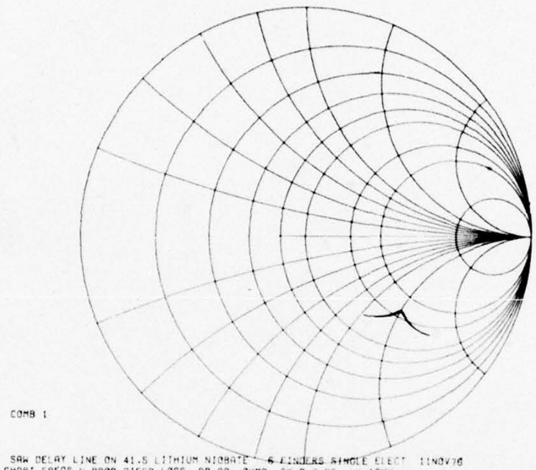


COMB 2

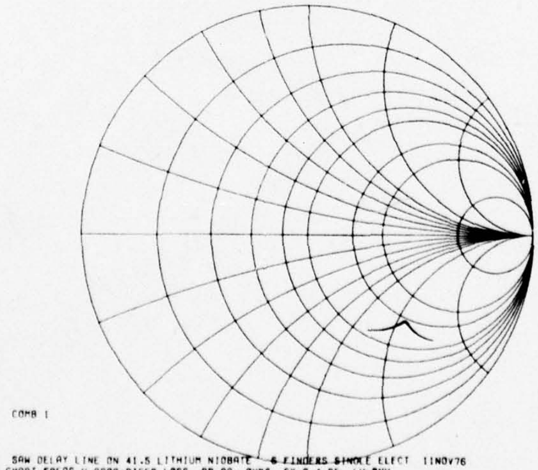
C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=75 OHMS CX=0.6 PF LW=15NH



C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=90. OHMS CX=0.3 PF LW=8NH



C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=90. OHMS CX=0.3 PF LW=10NH



C3N=2 SAW DELAY LINE ON 41.5 LITHIUM NIOBATE 6 FINGERS SINGLE ELECT 11NOV76
SMITH CHART FREQS W PROP+DIFFR LOSS RP=90. OHMS CX=0.4 PF LW=8NH

METRIC SYSTEM

BASE UNITS:

Quantity	Unit	SI Symbol	Formula
length	metre	m	...
mass	kilogram	kg	...
time	second	s	...
electric current	ampere	A	...
thermodynamic temperature	kelvin	K	...
amount of substance	mole	mol	...
luminous intensity	candela	cd	...

SUPPLEMENTARY UNITS:

Quantity	Unit	SI Symbol	Formula
plane angle	radian	rad	...
solid angle	steradian	sr	...

DERIVED UNITS:

Quantity	Unit	SI Symbol	Formula
Acceleration	metre per second squared	...	m/s
activity (of a radioactive source)	disintegration per second	...	(disintegration)/s
angular acceleration	radian per second squared	...	rad/s
angular velocity	radian per second	...	rad/s
area	square metre	...	m
density	kilogram per cubic metre	...	kg/m
electric capacitance	farad	F	A·s/V
electrical conductance	siemens	S	A/V
electric field strength	volt per metre	...	V/m
electric inductance	henry	H	V·s/A
electric potential difference	volt	V	W/A
electric resistance	ohm		V/A
electromotive force	volt	V	W/A
energy	joule	J	N·m
entropy	joule per kelvin	...	J/K
force	newton	N	kg·m/s
frequency	hertz	Hz	(cycle)/s
illuminance	lux	lx	lm/m
luminance	candela per square metre	...	cd/m
luminous flux	lumen	lm	cd·sr
magnetic field strength	ampere per metre	...	A/m
magnetic flux	weber	Wb	V·s
magnetic flux density	tesla	T	Wb/m
magnetomotive force	ampere	A	...
power	watt	W	J/s
pressure	pascal	Pa	N/m
quantity of electricity	coulomb	C	A·s
quantity of heat	joule	J	N·m
radiant intensity	watt per steradian	...	W/sr
specific heat	joule per kilogram-kelvin	...	J/kg·K
stress	pascal	Pa	N/m
thermal conductivity	watt per metre-kelvin	...	W/m·K
velocity	metre per second	...	m/s
viscosity, dynamic	pascal-second	...	Pa·s
viscosity, kinematic	square metre per second	...	m/s
voltage	volt	V	W/A
volume	cubic metre	...	m
wavenumber	reciprocal metre	...	(wave)/m
work	joule	J	N·m

SI PREFIXES:

Multiplication Factors	Prefix	SI Symbol
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
100 = 10^{2}	hecto*	h
10 = 10^{1}	deka*	da
0.1 = 10^{-1}	deci*	d
0.01 = 10^{-2}	centi*	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	μ
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a

* To be avoided where possible.

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